PATH medical GmbH

Senti and Sentiero

HOW-TO MANUAL

HINTS AND CLINICAL APPLICATION METHODS AND SCIENTIFIC BACKGROUND

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Part I

How to use the methods provided by Senti and Sentiero

Senti and **Sentiero** are portable hand-held device designed for facilitating the assessment of hearing impairment in infants, children, and adults. The purpose of the How-to Manual is to get familiar with all the methods present on both devices, especially the full featured **Senti** and **Sentiero.** The devices are modular, so subsets of the methods are availabel.

This how-to manual has two parts. Part I describes how to use the different methods in praxis in separate chapters. Part II describes general aspects of the methods.

1 Overview

This How-To-Manual is providing additional information on **Senti** and **Sentiero** - seen from a daily use perspective from the end user. It does not replace the user manual, which is provided together with the device and which already describes the function of the device.

Sentiero offers both psycho-acoustical and physiological test procedures which are based on conventional and image-based pure-tone audiometry, speech (logatome) intelligibility, and otoacoustic emissions.

Psycho-acoustical test modules are:

- **MAGIC** (Multiple-choice Auditory Graphic Interactive Check)
  Image-based and self-controlled pure-tone audiometry

- **PTA** (Pure Tone Audiometry)
  Conventional pure-tone audiometry (class 3/4 audiometer)

- **SUN** (Speech Understanding in Noise)
  Vowel-Consonant-Vowel logatome test

Physiological test modules are.

- **DPOAE Threshold**
  Estimating hearing loss by means of extrapolated DPOAE I/O-functions

- **Quick DPOAE**
  Indicating the presence of a valid DPOAE at one ore more selected primary tone levels

- **TEOAE Diag**
  Performing conventional click-evoked otoacoustic emissions measurments

● **TEOAE Quick**
Performing TEOAE measurement by using an automated, statistical algorithm for response detection

Please note:
Placement of the transducers is important. Variation in earphone position up-down or front-back and leakage between earphone and ear may give rise to falsely poor hearing threshold levels, particularly at the highest frequencies. When using insert sound probes the probes must be placed such that there is no leakage between ear tip and outer ear canal. Ear probe ports must not be blocked with ear canal wax. Tests have to be performed in an acoustic shielded booth or in a separate quite room. Sentiero must not be used in cases of external otitis (outer ear canal infection) or in cases where the outer ear canal is occluded with cerumen (ear wax). Therefore, otoscopy is advised before measurement (especially before sound probe insertion).

2 MAGIC - How to use

Play-audiometry is a well established method in pediatric audiology. However, the test procedure, in which the child must be continuously observant, is exhausting, and the task (usually placing a peg in a pegboard) is varied only little. In contrast, image-based and self-paced test procedures can considerably enhance the child's attentiveness.

MAGIC ('Multiple-choice auditory graphic interactive check') is a new tool with which pure-tone thresholds can be determined in a playful way. Using a self-controlled measuring procedure the child's attentiveness is significantly enhanced.

Intended use of MAGIC is to determine pure-tone thresholds in young children, preschool and school children.

MAGIC can be performed at frequencies between 0.250 kHz and 8 kHz. Different animals represented different frequencies: Cow 250 Hz, bear 500 Hz, elephant 1 kHz, cat 2 kHz, sheep 3 kHz, mouse 4 kHz, bird 6 kHz, dolphin 8 kHz. Each animal is presented in three variants. "Neutral" to start the sound presentation, "healthy" and "sick" for indicating the two conditions 'heard' and 'not heard'. Before measurement a story is told such that the child is instructed that healthy animals will make sounds and sick animals are not able to. The child has the task to decide and categorize. So the child is the 'doctor'. This can also help to put off the pressure of the child, because it's not him/her to be diagnosed, but he/she will diagnose the animals' ability to give sounds.
The child has the task to decide and categorize. So the child is the 'doctor'.The test procedure progress is visualized by a shelf, from which the current test animal is selected. The test is controlled by the child itself via touch screen. This includes sound presentation as well as input if the sound was heard (healthy animal) or not (sick animal). The examiner can supervise the measurement and assist the child with the entry when indicated. The examiner can also intervene in the measurement procedure at any time or can do a retest at any frequency whenever necessary.

Please note:

Children which are not expected to be able to perform the test or are not able to react to the sound in a proper way DPOAE Threshold measurement is advised (see below).

Two different modes are available:

MAGIC Audiogram
In MAGIC Audiogram mode stimuli are delivered at different stimulus levels. Threshold is determined by an automatically controlled bracketing procedure. After finishing the test, pure-tone thresholds are displayed in an audiogram form with areas of different colours indicating different degrees of impairment.

MAGIC Quick-Screen
In MAGIC Quick-Screen mode the test is performed at only one stimulus level (screening level) which can be selected by the user.

Stimuli can be delivered via headphones or insert sound probes.

To get familiar with the test procedure an instruction is necessary. There are always three animals used for instruction phase. The following course of actions is advised:

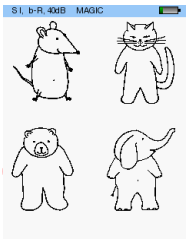
Instruction to the child	Examiner's task
"Choose an animal from the screen."	Select a stimulus level which is expected to be higher than the child's threshold. Should be done in settings before starting the test. Standard setting is 60 dB.
"Press the animal's belly. When pressing the belly the animal will make a sound"	
"Do you hear the sound?"	
"Each time you press the belly the animal makes a sound."	Ask the child to push the belly several times.
"The animal makes a sound, but	A stimulus level which is 20 dB

Instruction to the child	Examiner's task
the sound is now lower. Press the belly. Do you hear the sound?"	lower is selected automatically. No interaction needed.
"This animal does not make a sound. You cannot hear anything."	A 'muted' tone is given. The 'unheard' (animal with scarf) is to be pressed.
	Start the test.
	If the child is not able to react in the right way repeat instruction phase using the Re-Instr. button in the settings menu.

In the following, the course of actions and the corresponding settings for instruction (Instruction Phase) and measurement (Measurement Phase) is described in detail. Also, it is described how test results are displayed (Test Results).

Instruction Phase in images:

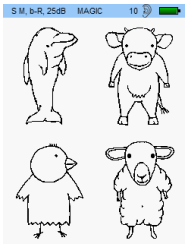
The introduction phase starts automatically and makes the test person acquainted with the test procedure. During the introduction phase the letter "I" is displayed in the header.
A story told by the tester will motivate the child for the test and will explain the test procedure.



➢ Select one animal from the screen.

The order in which the different animals are selected is optional!
Different animals represent different frequencies.

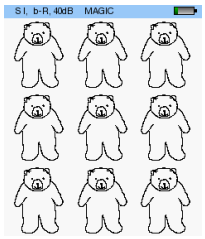
(: 500 Hz, : 1000 Hz, : 2000 Hz, : 4000 Hz)



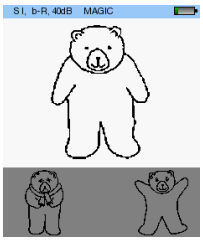
(: 250 Hz, : 3000 Hz, : 6000 Hz, : 8000 Hz)

The introduction phase consists of three steps:

First step (at stimulus level which should be heard easily):

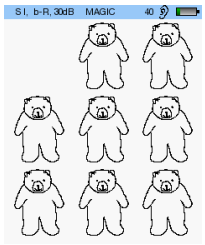


- Select one animal.

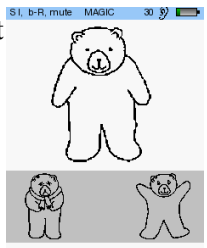


- Click on the big animal to elicit a tone.
- If the tone was heard, press the happy animal key (botton right).
- If the tone was not heard, press the unhappy animal (botton left).

Second step (lower level):

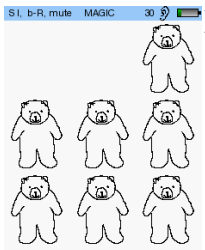


- Select the next animal.

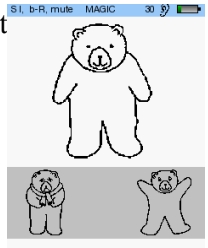


- Click on the beig animal to elicit a tone.
- If the tone was heard, hit the happy animal key, if not, hit the unhappy animal with the scarf.

Third step (mute):



- Select the next animal.



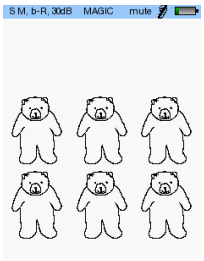
- Click on the big animal. No tone will be heard. In the Instruction phase, the third animal is muted to test the manual input of the tested person.Select the next animal.

Additional instruction phases can be manually triggered by pressing

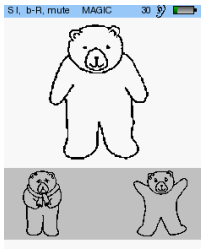
in settings (in the screen footer).

Measurement Phase:

After the successful completion of the instruction phase, the measurement phase with adaptive level presentations starts automatically.



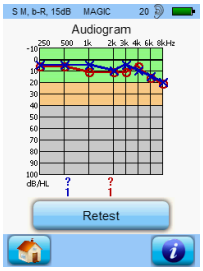
- The child shall now select the next animal from the rack.



- The child shall hit the happy animal if the tone was heard or hit the sad animal if the tone was not heard.
- If the child seems indecisive, ask him/her to hit the big animal again to repeat
  the sound.
- Continue selecting the next animals until the automatic end of the test.

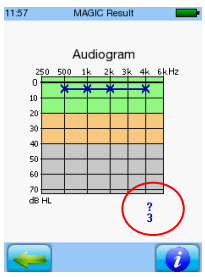
A mute tone will be presented randmomly with every 4th to 6th animal to verify the correctness of the child's answers and to keep up the children's motivation.

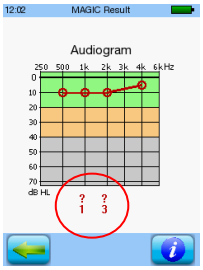
MAGIC test results:



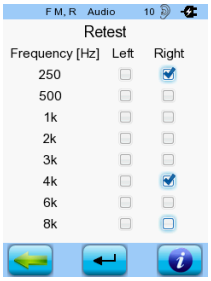
- Test results are displayed in a color-coded audiogram.
- Press

to do a retest. The test results will be stored.
- The test results will be saved automatically.





- Question marks - ? 1 (for right ear) or ? 1 (for left ear) - appear underneath the audiogram if a muted animal was marked as heard during the measurement phase.
- The figure underneath the question mark displays the number of these answers.



- Select the frequency and the ear (left or right).
- To do the retest (at selected frequency levels and selected ear(s) confirm data (black arrow).
- The test results will be saved.
- Press the green arrow to quit the screen.

3 PTA - How to use

PTA ('Pure-tone audiometry') is the key hearing test to identify hearing threshold levels of an individual, enabling determination of the degree, type (conductive or sensorineural) and configuration of a hearing loss. PTA is a subjective, behavioural measurement of hearing threshold, as it relies on patient response. Therefore, PTA is used on adults and children old enough to cooperate with the test procedure.

Usually, PTA is performed by using an audiometer in the form of a tabletop unit. Sentiero provides audiometer facilities in the form of a handheld device meeting all demands of a basic diagnostic audiometer of class 3 according to DIN IEC 60645-1.

In screening PTA, the test results show whether the hearing threshold levels are better, equal to, or worse than the screening level used. The subject passes the screening test according to predefined criteria, e.g. a pass occurs if all tones are heard in each ear. Screening at certain selected levels and frequencies is faster than measuring hearing threshold levels. In order to perform PTA screening with Sentiero, test frequencies and predefined levels can be selected by the user.

Intended use of PTA is to determine pure-tone thresholds in preschool and school children. Also, PTA can be used in clinics (bed-side use, ambulances), outpatient clinics, and occupational medicine.

Three different modes are available depending on the device’s license key:

PTA 4
for assessing air-conduction pure-tone thresholds at frequencies 0.25, 0.5, 1, 2, 3, 4, and 6 kHz. Stimulus level can be set from 0 to 70 dB HL.

PTA 4 advanced

for assessing air-conduction pure-tone thresholds at PTA 4 frequencies + 8 kHz. Stimulus level can be set from -10 to 100 dB HL for 0.5, 1, 2, 3, and 4 kHz; from -10 to 90 dB HL for 6 kHz; from -10 to 80 dB HL for 8 kHz; from -10 to 70 dB HL for 0.25 kHz.

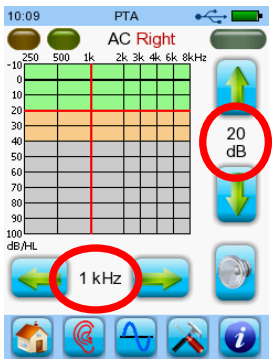
PTA 3
for assessing air-conduction and bone-conduction pure-tone thresholds. Stimulus settings for air-conduction are the same as those for PTA 4 advanced. Maximum stimulus levels for bone conduction are as follows: 35 dB HL for 0.25 kHz, 50 dB HL for 0.5 kHz, 60 dB HL for 2 kHz and 3 kHz, 50 dB HL for 4 kHz, 40 dB HL for 6 kHz and 35 dB HL for 8 kHz.

Air conduction stimuli can be delivered via headphones or insert sound probes. However, when using insert sound probes maximum stimulus level is by 10 dB lower with the exception at 0.25 kHz.

Please note:
As PTA is a psycho-acoustical test method the ability, willingness, and concentration of the subject to co-operate are essential.
Be aware, that there can be a large discrepancy between PTA and real threshold in infants and young children. In these cases it is advised to perform DPOAE Threshold.

In the following, the use of the PTA 4, PTA 4 advanced, and PTA 3 is described in detail.

Measuring with PTA:



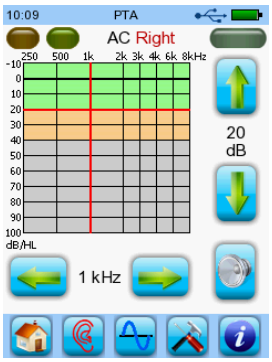
The currently selected sound level is shown in between the arrows.

Step 1:

- Select the **stimulus level** with the arrows.

Step 2:

- Select the **frequency level** with the arrows.



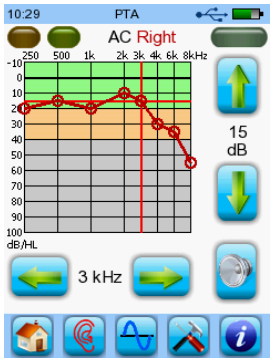
Step 3:

- Press to elicit a stimulus.

  (**Note:** The tone will be played as long as is pressed; turns when the tone is elicited)
  The patient response button turns light green when the patient marks the tone as heard with the patient response button. (Only for PTA 4 Extended).

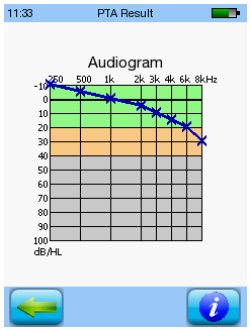
Step 4:

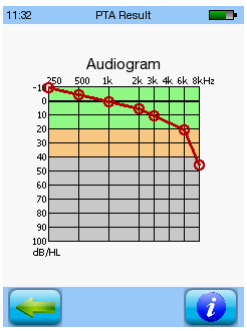
- Then click in the touch screen diagram to confirm the currently selected stimulus level as **hearing threshold** if the tone was heard. Or adjust the stimulus and frequency level shown in step 1 and 2.
- Continue setting the next hearing threshold like shown in step 1-4.



- Press in the screen footer to change the ear (red for the right ear or blue for the left ear).

PTA test results:





PTA test results are displayed as a color coded standard audiogram for the left and for the right ear.

4 OAE - How to use

OAEs ('Otoacoustic emissions') are weak sounds generated by the outer hair cells (OHCs) of the inner ear. They are measured by means of a sensitive microphone within a sound probe placed in the outer ear canal. Evoked OAEs are generated by either transient (clicks and tone bursts) or stationary stimuli (tones) delivered via loudspeakers within the sound probe. Transiently evoked OAEs (TEOAEs) represent the sum of the pulse responses of outer hair cells (OHCs) along the cochlea. Distortion product OAEs (DPOAEs) represent cubic distortions of OHCs when stimulated simultaneously by two tones with frequencies f1 (lower frequency) and f2 (higher frequency). DPOAEs arise directly from the frequency-selective compressive non-linearity of OHCs. The two tones interact in the cochlea close to the characteristic place of f2. Thus, DPOAEs can be applied as a probe for frequency-specific assessment of cochlear dysfunction at the f2 place. TEOAEs disappear at a hearing loss higher than approx. 15 dB HL in case of a conductive hearing loss and approx. 30 dB HL in case of a cochlear hearing loss. DPOAEs can not be detected at a hearing loss higher than approx. 25 dB HL in case of a conductive hearing loss and approx. 50 dB HL in case of a cochlear hearing loss, respectively. Before each OAE measurement calibration of the ear probe is automatically done. In cases where the sound probe is not inserted properly or sound probe ports are blocked a warning (“incomplete”) will appear.
Four different OAE modes are available:

DPOAE threshold (patented method)
for getting frequency- specific and quantitative information of cochlear function at a hearing loss of up to 50 dB HL. Threshold estimation is automatically done by extrapolating DPOAE I/O-functions obtained at primary tone levels between 15 and 65 dB. Test frequencies are 1.5, 2, 3, 4, 6, and 8 kHz. At frequencies at which not more than three valid DPOAEs per test frequency are measurable no extrapolation is done. In this cases simple threshold estimation is automatically performed. The lowest stimulus level at which a valid response occurs is now used as reference to the estimated threshold. For eliciting DPOAEs, a special parameter setting (scissor paradigm) is used which accounts for the different compression of

the primary tones on the basilar membrane (for more detail see How-To Manual Part II). Progress of measurement and noise floor are indicated for current measurement. Filled vertical bars indicate at which levels valid DPOAE were measurable. Open box symbol indicates at which frequency and level DPOAE measurement is running. Estimated thresholds are presented in an audiogram form (DPOAE audiogram). Type of estimation is indicated by different symbols. In contrast to TEOAEs, common DPOAEs, and click evoked brain-stem potentials, DPOAE audiograms are able to quantitatively assess the hearing loss. Test time for establishing a DPOAE audiogram takes a couple of minutes only. Thus, DPOAE audiograms can serve as a new tool for bridging the gap between screening and audiological testing. Clinical application of DPOAE audiograms are presented and discussed in How-To Manual Part II.

DPOAE Quick
for measuring DPOAEs at user defined test frequencies and levels. Frequencies and levels can be chosen from a frequency-level matrix. Two different protocols are available: Screening (at a selected screening level) and individual diagnostic (multiple selections of stimulus parameters). Progress of measurement and noise floor are indicated for current measurement. Increasing vertical bars show if there is a valid response at the different test frequencies. DPOAEs are measured automatically at the different test frequencies. However, test frequencies can be skipped by the examiner. Results are displayed in the frequency-level matrix indicating valid, invalid, and skipped measurements.

TEOAE Diag
for measuring TEOAEs in a time window of 3 to 13 ms at a fixed stimulus level. Progress of measurement and noise floor are indicated during measurement. Also stimulus stability and number of rejected frames (artefacts) are displayed. Criteria for proving response as valid can be chosen in five half-octave bands their centre frequencies being 1, 1.5, 2, 3, and 4 kHz. This is done by setting a specific signal-to-noise ratio (3, 6, or 9 dB) for each frequency band. Time course and frequency spectrum of the response are shown on the screen. Also, noise and SNR are indicated for the different frequency bands. If the test criterion is reached “valid response”, if not “no response” appears on the screen. Termination of the measurement by the user (stop) is indicated by “incomplete test”. It is a common rule in clinical practice to yield a stimulus stability of more than 80%. Artefacts shall be lower than 20 %.

TEOAE Quick
When running TEOAE Quick criteria for proving response as valid are fixed (no user defined criteria). If the test criterion is reached “valid response” is indicated, if not “no response” appears on the screen. Termination of the measurement by the user (stop) is indicated by “incomplete test”. Like in TEOAE Diag progress of

measurement and noise floor are indicated during measurement. Also stimulus stability, number of rejected frames (artefacts), and measuring time are displayed. Time course and frequency spectrum of the response are shown on the screen during measurement.

Intended applications of OAEs are as follows:

- Confirmation of cochlear hearing loss after newborn hearing screening
- Assessment of hearing function in infants who are identified at risk for congenital or late-onset hearing loss
- Frequency-specific and quantitative evaluation of mild and moderate hearing loss in infants
- Topological diagnostics
- Quick test for getting information on hearing capability in preschool and school children
- Early detection and monitoring of OHC impairment after noise or ototoxic drug administration
- Indisputable proof of a noise-induced hearing loss for medical opinions
- Identifying persons who are simulation a hearing loss

Please note:
Since OAEs are the by-product of the non-linear sound amplification process of OHCs in the cochlea they can only serve as a measure for evaluating cochlear integrity.
Microphone noise, physiological noise (breathing, blood flow), and external noise do not allow proper OAE measurements at low stimulus levels. At lower frequencies, OAE measurements are not reliable even at high stimulus levels. To achieve low noise-floor levels OAE measurements have to be done in a sound-attenuating booth especially when close-to threshold stimulus levels are used.
Make sure that insertion of sound probe must be done without any leakage between sound probe and ear canal. Leakage is indicated during calibration procedure which is done automatically. If there is leakage, low frequency sound components can not be delivered to the cochlea properly and hence no apical and medial OHCs will contribute to OAE response. Blockage of sound probe ports is indicated when performing calibration.
Be aware that high-frequency TEOAE components get lost as a result of the windowing procedure which is done for excluding stimulus sound components from the response. As a result, OHC functionality can not be determined in the basal region of the cochlea when using TEOAEs. Therefore, a high-frequency hearing loss can not be detected by TEOAEs. Also note that valid TEOAE responses can be present in ears with a mid-frequency hearing loss (e.g. congenital hearing loss). The problem with TEOAEs here is that infants with congenital hearing loss are

overseen and the hearing loss is detected later in life. In general, to get more frequency-specific and quantitative information on the hearing loss it is advised to perform DPOAE threshold measurements (for case examples see How-to Manual Part II).
Due to standing waves in the outer ear canal stimulus and response can not always be reliably be determined and thus DPOAE thresholds do not always match pure-tone thresholds. This is true especially for high ear canal volumes. If this is the case a discrepancy between DPOAE thresholds and PTA thresholds mainly occurs in the mid-frequency region around 3 kHz and at the higher test frequencies (> 6 kHz).
Very important: if there is no OAE response the following pathologies are possible: sound conductive hearing loss, cochlear hearing disorder of at least 30 dB hearing loss (TEOAE) or at least 50 dB hearing loss (DPOAE). Therefore, tympanometry, auditory brain-stem responses and auditory steady-state responses have to be performed to assess the type and the degree of the hearing loss.

In the following, the use of the different OAE tests is described in detail.

OAE:

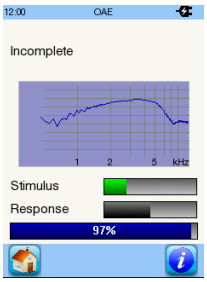
➢ Press DPOAE to start DPOAE menu:

➢ Press TEOAE to start TEOAE menu:

DPOEA Threshold:

- Press to select the frequencies you want to test:

- To start the measurement, please choose between right and left ear.

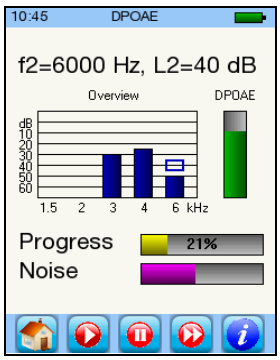


- A calibration of the ear probe will first be performed before the measurement starts.

- If the probe is not placed properly in the ear canal, the message “incomplete” will appear on the display. In this case, please correct the position of the probe.

The following speaker test detects the proper functionality of the speakers.

DPOAE I/O functions are measured at the following frequencies: 1.5, 2, 3, 4, 6 and 8 kHz.
Before the measurement of each frequency stars, a fine adjustment is performed, in order to check at which frequency the emission can best be recorded.
DPOAE I/O functions are measured from L2 = 65 dB SPL in 10-dB-steps decreasing to L2 = 15 dB SPL.
If several values are measured a line of values is displayed, running from the bottom (high L2) to the top (low L2). L2 is reduced for as long as a DPOAE response occurs. If no response is recorded, L2 is increased automatically until 5 values are identified. For the estimation of the hearing threshold are needed at least three measuring points.



Display during measurement:

f2 current frequency; **L2** current level

time out (progress) bar : measuring time

noise bar: surrounding noise

open box symbol: current measuring point

filled vertical bars: previous valid measurement data

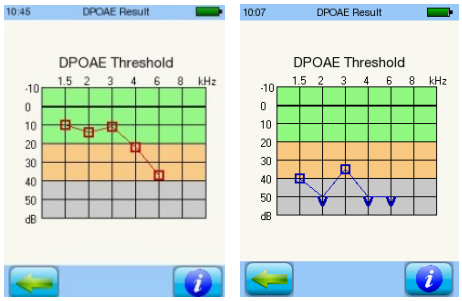
- Press (PAUSE), to interrupt the test
- Press (CONT.) to continue the test
- Press to skip a frequency

The measurement will continue with a 5 dB lower level or with the next frequency.

- Vertical green bar: validity of the DPOAE response at the current stimulus frequency and level started at the top of the screen.
- If a DPOAE response was identified as being valid, the vertical bar at the respective frequency is extended to the corresponding primary tone level L_2.
- The colors of the vertical bars in the diagram correspond to the standard color of the tested ear (red: right ear, blue: left ear).

DPOAE Threshold test result:

The **DPOAE-Audiogramm displays** the estimated **hearing threshold at different frequencies.**

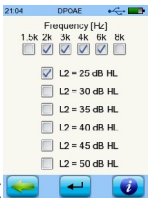


- : back to test result list

An arrow pointing down from the 50 dB line indicates that no sufficient emissions could be measured in order to fulfill the criterion. A hearing loss greater than 50 dB could be the case.

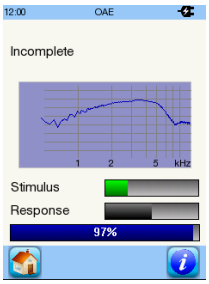
Note: In case DPOAEs are missing we recommend verifying the status of the middle ear with a tympanogram.

DPOAE Quick:

- Press to select the frequencies you want to test: 
- To start the measurement, please choose between right and left ear.

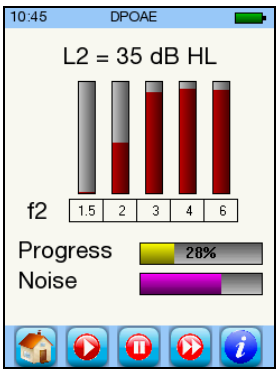
Select level and Quick DPOAE measurement:

- Select primary tone level L_2
- A single level or up to six different levels can be selected at once.
- confirm the selected levels and frequencies.
- Return to OAE selection.
- A calibration of the ear probe will first be performed before the measurement starts.



- If the probe is not placed properly in the ear canal, the message "incomplete" will appear on the display. In this case, please correct the position of the probe.

The following speaker test detects the proper functionality of the speakers.



After the tests, the measurement starts automatically by scanning the cochlea at the selected primary tone level(s) L_2 and at up to six frequencies (1500, 2000, 3000, 4000, 6000, and 8000 Hz).

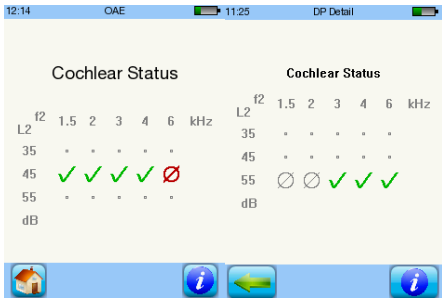
- Press to interrupt the test
- Press to continue the test after pausing
- Press to skip a frequency

- progress bar : measuring time
- noise bar: surrounding noise

After the measurement the measuring points of the single frequencies appear in logarithmic representation.

- **Vertical bars:** indicate the validity of the DPOAE response at the corresponding frequency f2.
- If the vertical bar reaches the top of the box the response contains a valid DPOAE signal according to the criterion.
- The color of the vertical bar corresponds to the standard color of the tested ear (red: right ear, blue: left ear).

Quick DPOAE test results:

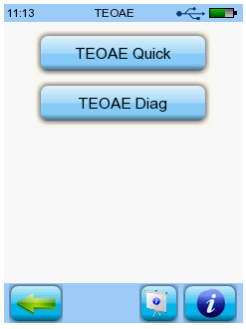


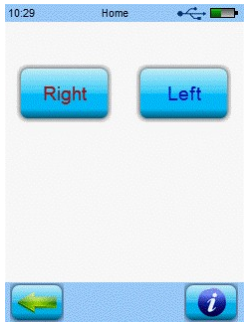
- : valid DPOAE test criterion
- : invalid DPOAE test criterion
- : test criterion was skipped
- : back to main menu
- : back to test results

TEOAE:

TEOAE Quick Mode or Diagnostic mode

- Select **TEOAE Quick/Diagnostic** on the screen, then select the ear side:.





Ear Volume calibration:

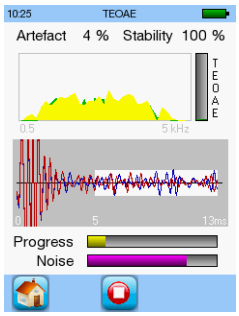
- The ear probe will first perform a ear volume calibration.

If the probe is not placed properly in the ear canal, the message "incomplete" will appear on the display. In this case, please correct the position of the probe.

Test Progress:

- The progression of the test can be viewed on the display.

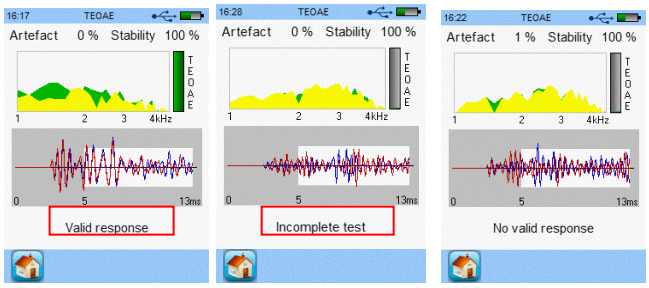
Display during measurement:



Stimulus stability (preferably > 80%)

Artifact (preferably < 20%)
Measuring time will depend on the test conditions noise and stability of the probe)

TEOAE Quick Test Result:



Upper Screen indicates OAE Signal Response (green) and noise floor (yellow) over frequency range . **Lower Screen** shows statistical signals A+B in a time window from 5 ms to 13 ms.

"Valid response": the statistical test criterion was reached

"**Incomplete test**": the test criterion was not reached

"No Response": the test criterion was not reached

TEOAE diagnostic mode result:

Upper Screen shows five TEOAE bands from 1 to 4 kHz the green response indicates that the selected criteria (3 or 6 or 10 dB) has been reached.

The criteria can be selected:
press in the footer to adjust the settings.

By **touching the upper screen** the measurement results toggles inbetween graphic and table display.

Lower Screen shows statistical signals A+B in a time window from 5 ms to 13 ms.
Result:
"Valid response": the statistical test criterion was reached.
"**Incomplete test**": the test criterion was not reached .
"No Response": the test criterion was not reached.

5 SUN - How to use

SUN is a novel self-controlled speech test designed for screening adults for hearing disability using a set of intervocalic consonants (VCVs). The test is designed such that it is self-convincing, fast, and of low cognitive load. To fulfil these criterions, the SUN test is specifically designed to assess the listening difficulty most commonly experienced by adults, i.e. to understand speech in noise. To minimize the duration of the test procedure, the sequence of stimuli presented in SUN test (i.e., the set of VCVs) has a fixed length, and the presentation levels of the test stimuli and noise are pre-determined. To minimize the cognitive load, the task of recognizing the stimuli in the SUN test is simplified by offering to the subject only three choices, for each VCV. Three-alternative forced choice procedure is used. Test person has to select via touch screen three alternative VCVs (e.g., aFa, aGa, aSa). VCVs are presented via headphones at different signal-to-noise ratios. The test gives a tri-modal outcome: hearing ability within normal range; hearing ability might be below the normal range; hearing ability might be well below the normal range.

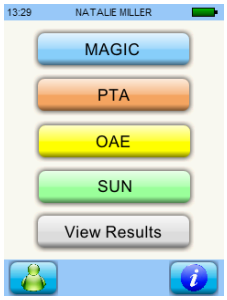
Intended us of the SUN test is to assess speech understanding in noise. The test was specifically designed for the early detection of age-related hearing loss. For description and evaluation of the test see: Paglialonga A., Tognola G., Grandori F. 2011. SUN-test (Speech Understanding in Noise): a method for hearing disability screening. Audiology Research 1:e13 Title, journal etc, Grandori et al. 2011). However, the SUN test can also be used as a self-controlled speech test for school children …..

Speech stimuli can be delivered via headphones, insert sound probes, or free field loudspeaker.

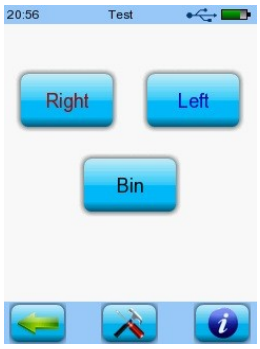
Please Note:
This test was initially designed for adults but it is also very likely to be used by school-kids in grade 1 (being able to read VCVs).

In the following, the use of the SUN test is described in detail.

Settings:

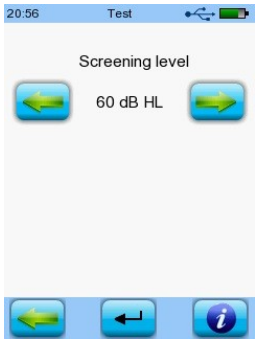


➢ Press SUN in the main menu to start measuring with SUN.



➢ Select the ear you want to test:

- Bin (binaural)
- right ear
- left ear

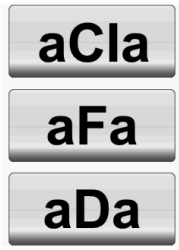


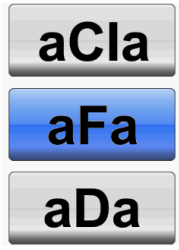
➢ After having pressed in the footer, select the hearing level you want to measure. Press or to change the current dB hearing level. The currently selected level can be seen in between and . The overall level is between 50 and 70 dB HL.

Measurement:

Select one ear or both ears to start the measurement.

➢ Different vcv-options are visualized. A voice will pronounce one of them.



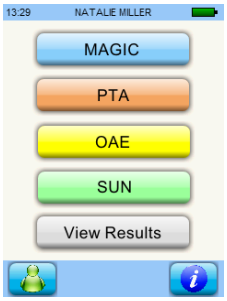


- The tested person shall select the heard pronunciation and press the according button.
- Going on with the measurement, the signal-to-noise-ratio will decrease.
- After 12 pronunciations, the test ends automatically and the results are shown.

SUN test results:

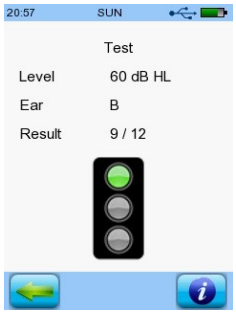
SUN scores the number of correctly identified stimuli. It determines whether hearing ability is within of below the normal range.

- The normal range is shown as a green signal light and lies between 9 and 12 out of 12 heard stimuli.
- If the hearing ability is slightly below the normal range, the score is shown as a yellow light. For this result the tested person must identify 7 to 8 out of 12 stimuli.
- Below the hearing ability the score is shown as a red light for which the tested person heard only 0-6 out of 12 stimuli.



- Click on View Results in the main menu in order to display the test results of the selected patient.

- Now press SUN B 2010-08-26 21:54 to see the details of the test result. R is the result for a tested right ear, L for the left and B for binaural.



- This result for example displays a SUN test with 60 dB on both ears. The tested person heard 9 out of 12 stimuli correctly. The green signal light stands for a normal hearing ability of the tested person.

6 ABR - How-to use

Auditory brainstem responses (ABRs) recorded from electrodes placed on the scalp represent the far field of potentials generated by the fiber tracts and nuclei of the ascending auditory pathway between the cochlea and the brainstem. The ABR latency epoch consists of up to seven prominent wave peaks which appear within the first 10 ms. Commonly ABRs are elicited by transient stimuli (click, tone-burst, chirp). ABRs represent the sum of synchronized neural activity of the ascending auditory pathway. Wave I and II stem from auditory nerve, wave III from cochlear nucleus, wave IV and V from lateral lemniscus and inferior colliculus (brain stem), and wave VI and VII from sub-cortical regions. Due to the fact that the velocity of the traveling wave running into the cochlea is highest in the basal region, click-evoked ABRs mirror mainly the activity of basal (high-frequency) cochlear regions. This is also true for low frequency tone-bursts and chirps when high stimulus levels are applied. Wave V has the highest whereas wave I the lowest amplitude. Wave amplitudes decreases wave latencies increases with decreasing stimulus level.

ABRs are a common clinical tool in audiology and neurology. Also, ABRs are used for newborn hearing screening when elicited at a distinct screening stimulus level (e.g. 35 dB nHL). Conductive and cochlear hearing loss exhibit different wave amplitude and latency patterns. Especially. wave V latency and threshold are used for audiological diagnostics in children or handicapped persons who are not able to reliably report on their hearing disability. The interpeak latency (IPL) between wave I and V represent the neural transmission time between cochlea and brainstem. IPL is therefore used for assessing retrocochlear pathology (eighth nerve and low brainstem lesions). It is important to note, that due to the maturation of the neural pathway IPL varies during the first year of life. The influence of age on ABRs in the elderly is a matter of controversy. While some authors have reported a change in IPL, others claim that there is no delay in neural transmission time with ageing. Also, no significant correlation was observed between the score of speech discrimination tests and IPL

Sensitivity of ABRs is quite low below 1000 Hz due to poor synchrony of neural aktivity in the apical region of the cochlea. Click-evoked ABR does not allow direct frequency-specific assessment of hearing loss. Click-evoked ABRs exhibit nearly normal patterns in patients with low- and/or mid-frequency hearing loss. Low-frequency stimulation at high stimulus levels will also stimulate basal sensory cells. Thus, assessment of low-frequency functionality is only possible at low stimulus levels. For getting more frequency-specific information DPOAE (at a

hearing-loss up to 50 dB) or tone-pip and chirp-evoked ABR have to be used. However, when applying low-frequency stimulation at high stimulus levels the basal region of the cochlea is also stimulated. Thus, frequency specificity of ABRs is restricted. Compared to ABRs, auditory steady-state responses (ASSRs) – available in 2012 - provide better frequency specificity.

In patients with hearing loss wave I may be missing. In these patients, determination of IPL is not possible and thus neural disorders can not reliably be assessed. Correct placement of electrodes is crucial in order to yield optimal ABR patterns. Due to the fact that electro-magnetic fields have impact on ABRs proper measuring conditions are essential. Proper measuring conditions are present if ABRs are measurable down to 10 dB nHL in a young normally hearing subject.

Intended clinical applications of ABRs are as follows:

- Topological diagnostics - assessment of peripheral and central sound processing on the auditory pathway up to the brainstem along with other audiological tests
- Identification of neural disorders (eight nerve and low brainstem lesions) on the auditory pathway
- Non frequency-specific determination of hearing loss within mid-frequency region when using clicks
- Determination of hearing loss within different frequency regions when using low-, mid-, and high-frequency chirp-stimuli

In the following, the use of ABR test is described in detail.

Corresponding button names and icons are as follows:

	ABR
	Settings
	Enter
	Play
	Pause
	Skip
	Left/right
	Back
	I III V
	Print
	Info
	I/III/V
	Set

6.1 Preparation of the patient to be tested

- Advise the subject to lay as comfortable as possible to avoid muscle activity.
- Clean the skin where the electrodes will be placed.
- Place electrodes.

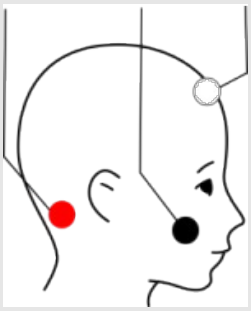


Fig. 1a: Screen pictogram

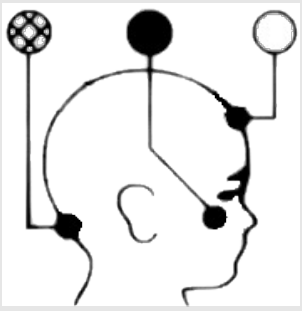


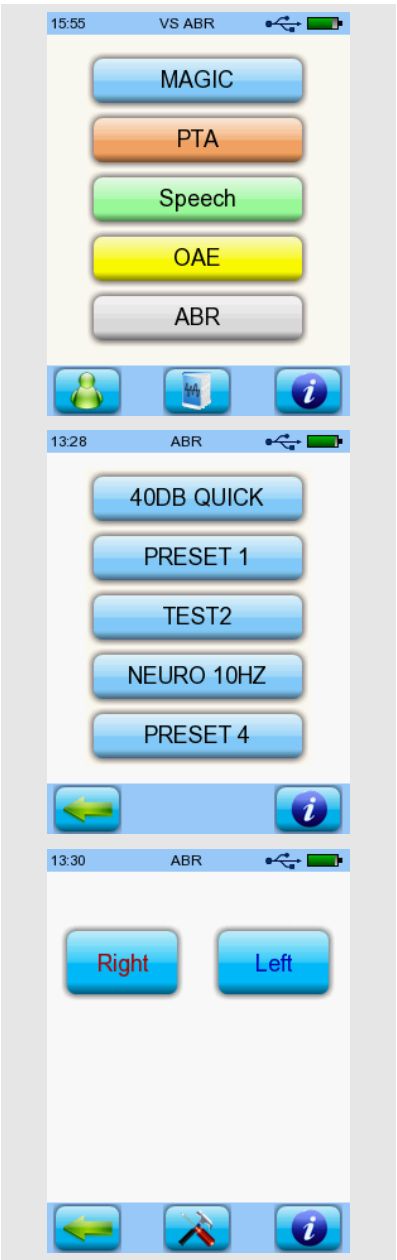
Fig. 1b: Cable pictogram

There are several possibilities to place the electrodes. The position of the electrodes affects waveform morphology and latency. Best electrode position for yielding maximum wave amplitudes is vertex and ipsilateral mastoid (vertical montage). Alternatively to the vertex position, forehead position for placing the vertex electrode is possible (see Fig. 1a and 1b). However, in this case ABR amplitude is slightly decreased. Despite this fact forehead is preferred in practice, especially in patients where vertex electrode placement is inconvenient because of hairs.
Wave I amplitude may be larger in a horizontal montage (mastoid to mastoid) than in the standard vertical montage (vertex to mastoid).
Reference electrode (black) is usually placed on the cheek.
Since Sentiero provides one channel, mastoid electrode cable must be changed when using vertical montage of the electrodes. If mastoid electrode is not changed, ABR is decreased in amplitude at the ear where mastoid electrode cable is connected to the contra-lateral ear.

Common placement of the electrodes for audiological testing:
Red(⊗): Mastoid, **Black (●)**: Cheek, **White (●)**: Forehead

6.2 Perform measurements

After placing the electrodes electro-acoustic transducers (headphones or insert phones) have to be fitted. Important: Please make sure that the red transducer is placed at the right ear and the blue transducer is placed at the left ear.
Plug the ABR cable connector in the white jack. Then connect the electrodes with the colored clips as described above (red: mastoid, white: vertex or forehead, black: cheek).

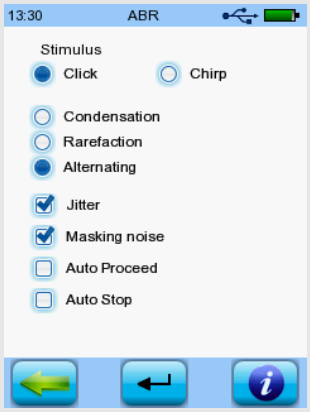


Start the measurement module by pressing “ABR”

Select one of the presets by pressing the appropriate button.

By pressing “Right” or “Left” the test ear is selected and the test starts.

Alternatively, the selected preset can be edited by pressing the “settings” button. There are 4 settings pages. Each has to be confirmed with “enter” in order to store the settings.



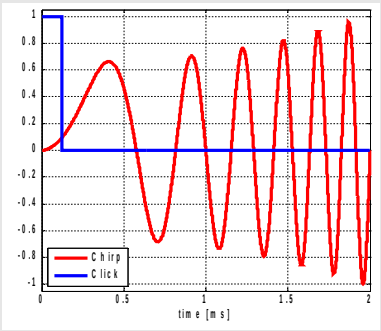


Fig. 2a Time domain

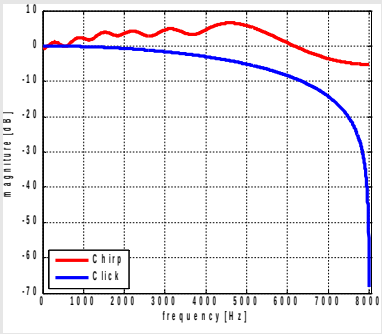


Fig. 2a Frequency domain

Select stimulus type "Click" or "Chirp"

Both clicks and chirps are broad-band stimuli. Broad-band stimuli are used to stimulate as many as possible sensory cells along the cochlea for getting highest neural activity on the nerve fibers. The band-width of a click (see frequency domain Fig. 2b, blue line) depends on stimulus duration (see time domain Fig. 2a, blue line). The shorter the click the higher is the band-width and with that the synchrony of neural activity on the auditory pathway. However, synchrony is decreased in the more apical regions of the cochlea in accordance with the decrease of the travelling wave velocity. In contrast to the click the chirp is a long-lasting stimulus which starts with low and ends with high-frequency signals (see time domain Fig. 2a, red line). Using this rising frequency chirp, the decrease of the travelling wave velocity along the basilar membrane is compensated resulting in an enhancement of the synchrony of neural activity and with that in higher response amplitudes. Chirp provides a broader frequency band compared to that of the click (see frequency domain Fig. 2a, blue and red line).

Select polarity: "Condensation" (C), "Rarefaction" (R) or "Alternating" (A)

Single-polarity stimuli (C or R) produce different initial movement of the basilar membrane. Initial firing of the nerves coincides with R stimuli resulting in different wave latencies and amplitudes with C and R. Thus different waveform morphology appears when using single- or alternating-polarity clicks.
Single-polarity click stimulation may evoke wave I with higher amplitude. However, when using single-polarity clicks the electrical signal of the electro-acoustic transducer interferes with the ABR. Therefore A click stimuli are preferred especially when using headphones. When using insert phones electrical artifacts are lower.

Select "Jitter"

"Jitter" will add a small random change in stimulus rate, which can reduce the sensitivity to certain electrical interference. ABR amplitude is known to be decreased at a constant stimulus rate due to adaptation. By enabling "Jitter" adaptation is reduced.

Select "Masking noise"

"Masking noise" will mask the contralateral ear. This is done to de-

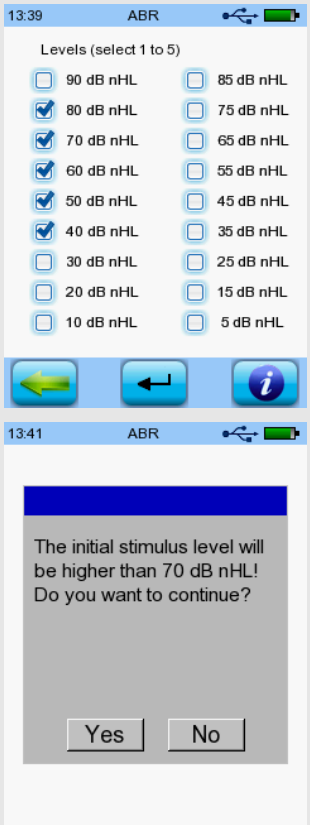
synchronize the stimulus related neural activity on the auditory pathway of the non tested ear which might be stimulated by cross hearing. It is recommended to always use this option especially in cases of asymmetrical hearing loss. The masking level is controlled by the device and depends on the stimulus level and the electro-acoustical transducer used.

Select "Auto Proceed"

"Auto Proceed" will proceed the measurement at the next stimulus level when significance is reached for the current measurement.

Select "Auto Stop"

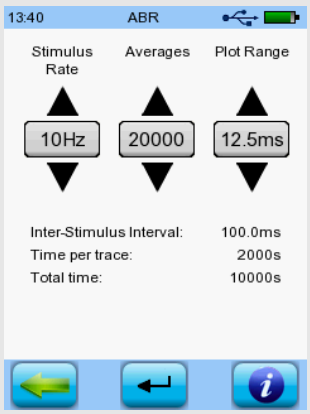
"Auto Stop" will abort the test sequence if no significant response could be recorded for two consecutive stimulus levels.



Select stimulus levels

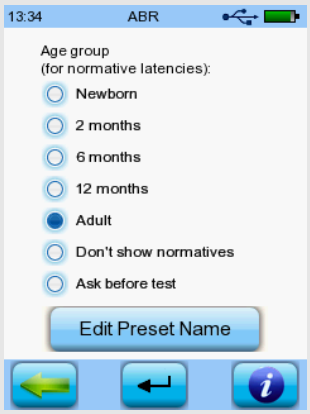
At the level selection screen 1 to 5 levels can be selected. Measurement will be started at the highest stimulus level.
ABR amplitude decreases and latency increases with decreasing stimulus level. In normal hearing subjects wave V latencies varies between about 5.6 ms (80 dB nHL) and about 9 ms (10 dB nHL). Standard deviation of latency is low at the higher stimulus levels (approx. 0.2 ms at 80 dB nHL) and high at the lower stimulus levels (approx. 0.7 ms at 10 dB nHL)

Initial stimulus levels higher than 70 dB nHL have to be confirmed prior to measurement!



Select the stimulus rate, plot range, and the number of averages per response

The inter-stimulus interval, the test duration per response and the estimated overall test duration will be shown as a result of the settings.
Changes in stimulus rate affect ABR latency and amplitude. With increasing stimulus rate wave amplitudes decrease and wave latencies increase. Please note: Wave I latency is less affected resulting in an increase of inter peak latencies with faster rates. For assessing neural disorders a rate of 10Hz is recommended. If wave V is the only component of interest (e.g. threshold determination), faster rates can be used.
With increasing number of averages quality of ABR measurement is increased. In quiet subjects and at good measuring conditions 2000 averages may be sufficient. If there is high muscle activity, high electrode impedance, ambient acoustical and electrical noise the number of averages has to be considerably increased, especially, at close-to-threshold stimulus levels.



Select age group

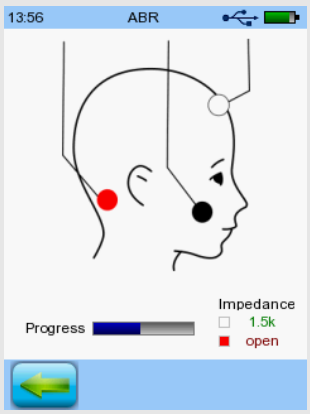
Several groups can be selected:
Newborn, *2 month*, *6 month*, *12 month*, *Adult*.
The selection will only affect the normative latency range which is different for the different age groups. Latency ranges are shown with the responses.

Further age group options: *Don't show normatives*, *Ask before test*.

By pressing "Edit Preset Name" the preset can be renamed.

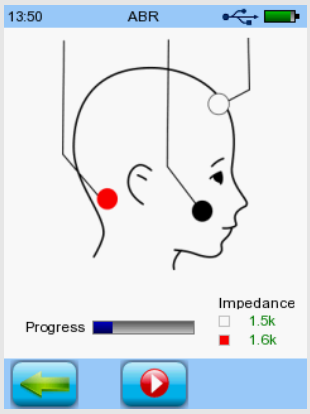
Type in the new preset name by using the screen keyboard. Confirm your input with "enter".

Continue Measurement



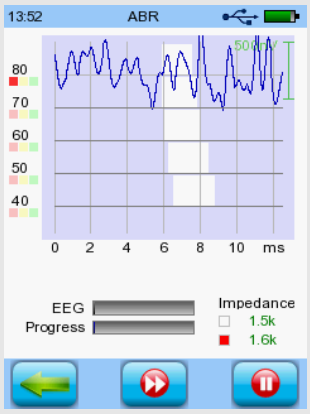
Before ABR measurement starts electrode impedance is checked. When the impedance is within an acceptable range (below 12 kΩ) a "play" button appears in the footer. To indicate good impedances the color of the impedance value will turn green if it is below 6 kΩ.

Please note: In neonates impedance may be higher than 6 kΩ because of tenderness of the skin. Also, unbalanced impedance affects the quality of ABR measurements.



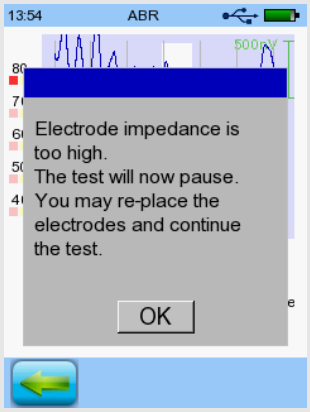
By pressing the "play" button ABR measurement at the highest selected level is started.

If the "play" button is not pressed or the impedance remains to high the device stops measuring after some seconds. In this case place the electrodes again and restart the test.



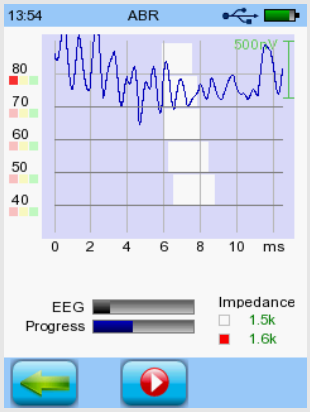
The currently measured response is shown in blue. All other responses are shown in gray. The right top corner indicates the current selected scale (100 to 2000 nV). It can be modified by wiping up and down inside the graph area after the measurement or in the "result view mode".

During the measurement the selected levels are shown on the left edge. The traffic light symbol to the left of each response indicate its significance. If "Auto Proceed" is selected the device will automatically proceed with the next measurement when significance of the current measurement was reached which is indicated by the green light. You may proceed at any time by pressing the "skip" button or wait until the maximum recording time per response is reached. After the maximum recording time is reached the device proceeds to the next stimulus level.

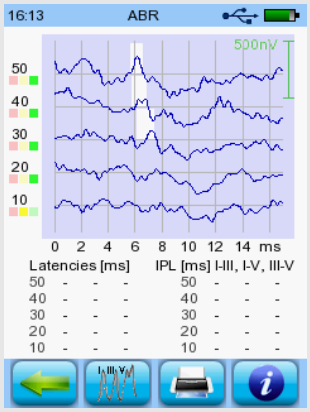


By pressing the "pause" button the measurement is paused and the "pause" button changes to the "play" button. To continue press "play".

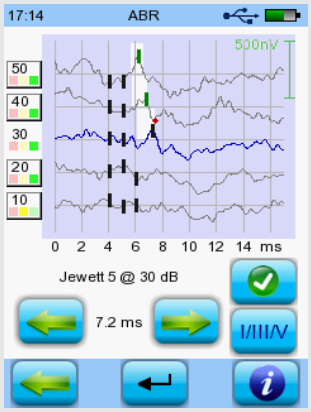
During the measurement the electrode impedance is measured periodically. If the value is too high the measurement is paused and a message "Electrode impedance is too high. The test will now pause. You may re-place the electrodes and continue the test" is shown.



In this case re-place the electrodes and press the “play” button to continue within the maximum recording time per response.



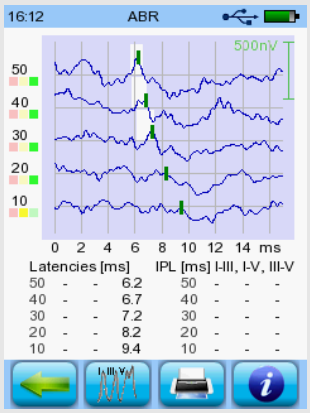
When the measurement has finished the ABR result panel is displayed which shows the responses at all selected stimulus levels. You may modify the scale by wiping up and down inside the graph area. The traffic light symbols to the left of each response indicate its statistical significance providing a suggestion for the responses to be valid.
If wave peaks were marked, the available absolute latencies (wave I, wave III, wave V) and relative latencies (IPL) will be shown in the lower panel. Different IPLs can be selected; Wave I-III, wave III-V, and wave I-V. Press the table area to display either latencies, recording parameters or quality data.



The footer shows now different buttons: “Back”, “I III V”, “print” and “info”. “Print” will print the results to the label printer. “Back” leads to previous screen. “Info” will show the online help.

“I III V” enters the edit mode, where you can mark peaks.

In the peak settings mode, you may mark wave peaks in each response manually. The active response can be selected by pressing the buttons to the left of each response.



“I/III/V” selects the marker to be modified indicated the red point on top of the marker.

“Set” makes a peak marker permanent, so that it will be stored with the test. The marker will turn green to indicate this.

“Left/right” moves the selected marker to set the latency of the corresponding wave. You may also set the marker by pressing on the desired latency position. Please note that order of the markers is always preserved with a minimum distance of 0.5 ms.

“Back” leaves the screen without saving new peak positions.

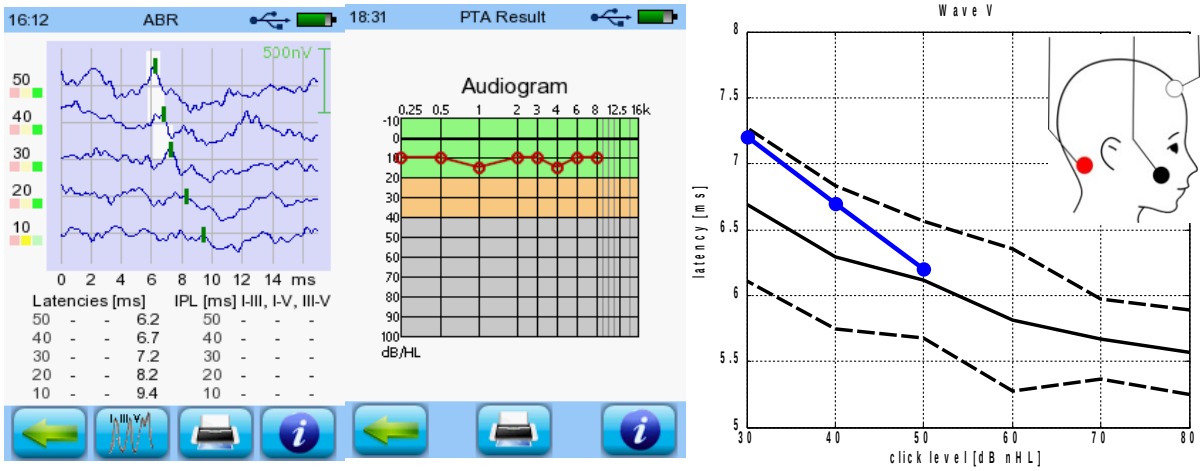
"Enter" confirms the changes and goes back to the regular ABR result display.

When opening a result from "result view" you have the same editing options as described above after a measurement.

6.3 ABR-case examples

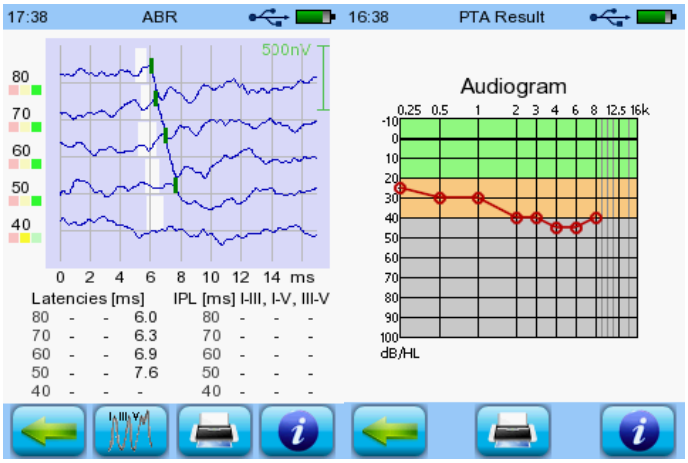
1. Normally hearing subject

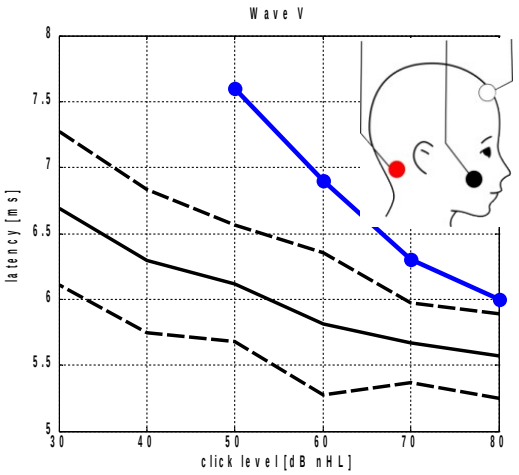
Click-evoked ABRs in a normally hearing subject at 50, 40, 30, 20, and 10 dB nHL stimulus levels. ABRs are measurable down to 10 dB nHL. Wave-V-latency increases and wave-V-amplitude decreases with decreasing stimulus level. Wave-V latencies are within normal range.



2. Conductive hearing loss

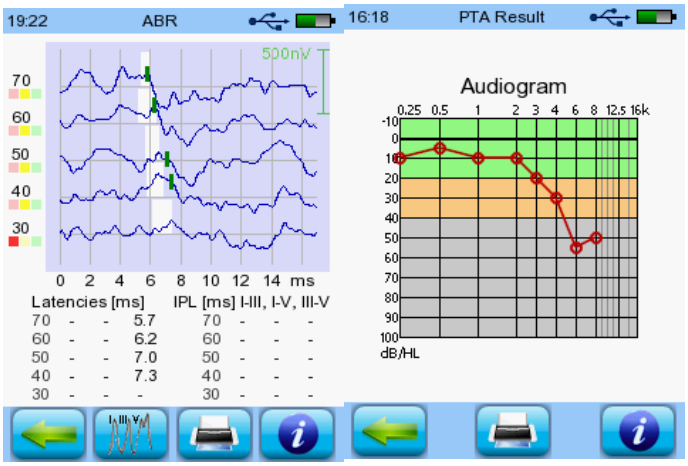
Click-evoked ABRs in a patient suffering from a conductive hearing loss at 80, 70, 60, 50, and 40 dB nHL stimulus levels. Wave-V latency is increased being out of normal wave-V latency range. ABR threshold is reached at 50 dB dB nHL corresponding to the hearing loss at high frequencies. Stimulus rate was set to 20 Hz, vertical electrode montage.

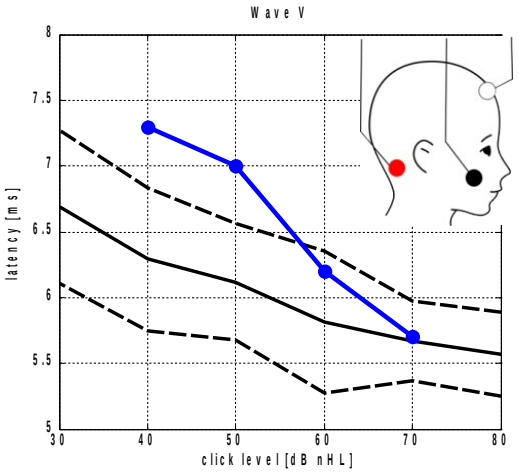




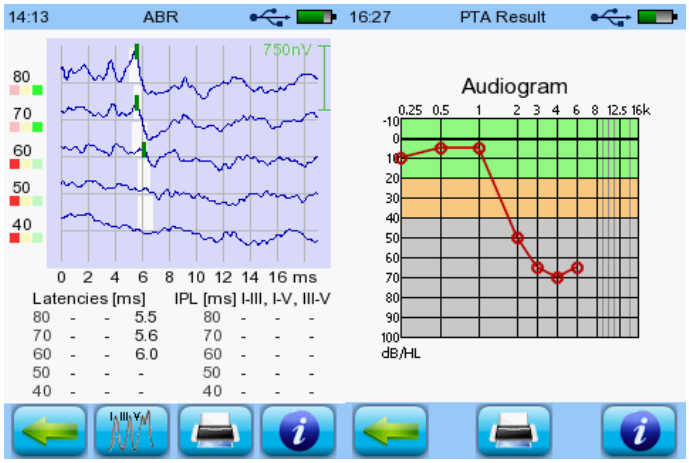
3. *Cochlear hearing loss*

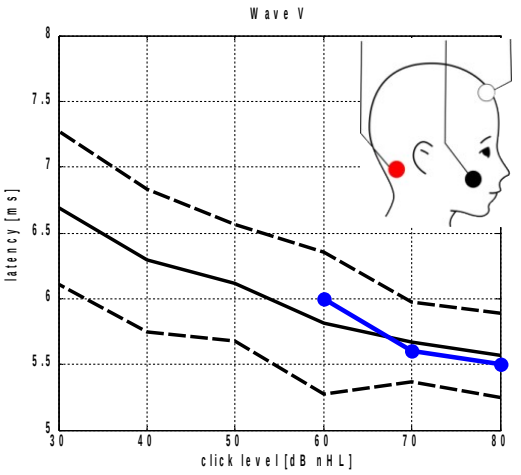
Click-evoked ABRs in a patient suffering from a moderate high frequency cochlear hearing loss at 70, 60, 50, 40, and 30 dB nHL stimulus levels. In comparison to the normally hearing subject ABRs appear with lower amplitude and slightly increased wave-V-latency. ABR threshold is reached at 30 dB nHL. The prolongation of latency at low stimulus levels corresponds to the propagation time of the travelling wave along the non-functioning basal part of the cochlea at these levels. Stimulus rate was set to 20 Hz, vertical electrode montage.



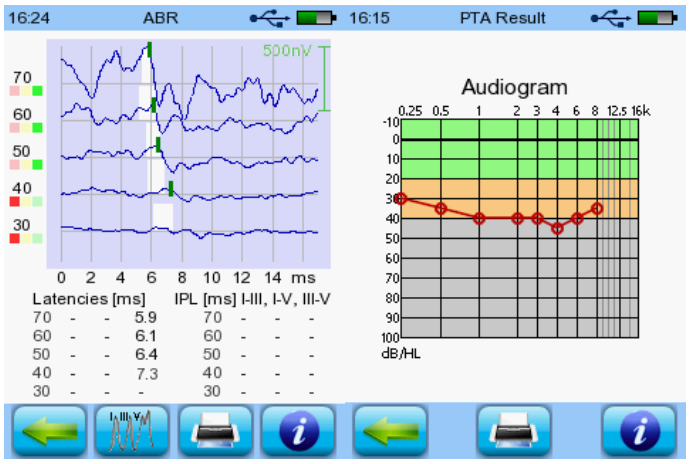


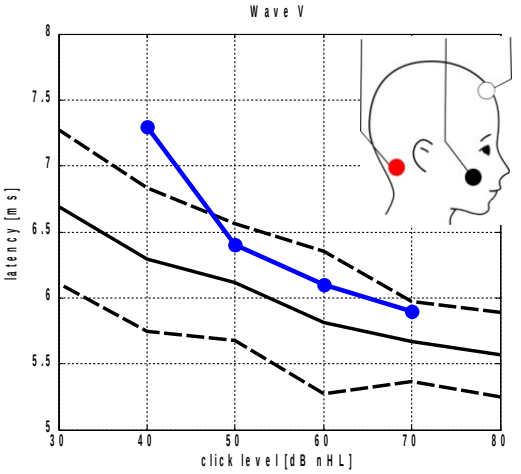
Click-evoked ABRs in a patient suffering from a severe high frequency cochlear hearing loss at 80, 70, 60, 50, and 40 dB nHL stimulus levels. ABR threshold is reached at 60 dB dB nHL approximately corresponding to the hearing loss at high frequencies. Low-frequency thresholds can not be assessed. Stimulus rate was set to 20 Hz, vertical electrode montage.





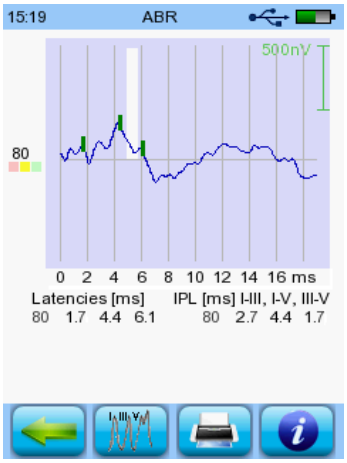
Click-evoked ABRs in a patient suffering from a pan-tonal frequency cochlear hearing loss at 70, 60, 50, 40 and 30 dB nHL stimulus levels. At all stimulus levels – with exception of the lowest one – latencies are within normal range. ABR threshold is reached at 40 dB dB nHL. Stimulus rate was set to 20 Hz, vertical electrode montage.

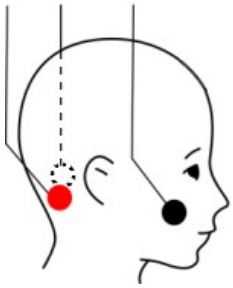




4. Retrocochlear hearing loss

Click-evoked ABRs in a female patient with neural disorders at 80 dB nHL stimulus level. ABR wave pattern is different compared to the normally hearing subject and the patients with cochlear or conductive hearing loss with respect to I-V IPL. I-V ILP is prolonged (4.4 ms) due to disturbed synchronisation of nerve fibers exceeding normal I-V interval (female: mean 3.8 ms, +/- 0,2 ms standard deviation; male: mean 4.0 ms, +/- 0,2 ms standard deviation). Stimulus rate was set to 10 Hz, horizontal electrode montage.


15:19
ABR
500nV
80
0 2 4 6 8 10 12 14 16 ms
Latencies [ms]
80 1.7 4.4 6.1
IPL [ms] I-III, I-V, III-V
80 2.7 4.4 1.7



Part II
Description of Methods

Description of the methods used in **Senti** and **Sentiero** is presented in the following. OAEs are higly sophisticated measuring procedures. Therefore, mechanism of OAE generation, recording, reproducibility, stimulus parameter settings, calibration procedures, and clinical applications are described in detail. Especially, the relationship between DPOAE thresholds and behavioral pure-tone thresholds is discussed. Addtionally, case examples for using DPOAE audiograms in clinical practice are given. A comprehensive list of references to the OAE literatur is also included. MAGIC and SUN are new tests. Only a few references to these tests are available. Performance of conventional pure-tone audiometry is described without references to the literatur.

7 MAGIC - Description of Methods

MAGIC (Multiple-choice Auditory Graphic Interactive Check) is a new image-based, self-controlled test for determining pure-tone thresholds in playful way.

Preliminary findings concerning feasibility and reliability of the test in children are described in a multi-centre study conducted at Department for Communication Disorders, ENT-Department of the University of Mainz Medical School´s hospital (Germany), at the ENT clinic of Klinikum rechts der Isar, Technische Universität München (Germany), and at Cyprus Audiology Center Nicosia (Cyprus) (Schirkonyer et al. @ DGPP → please also refer to our scientific publications on the support page or get into contact with us.

Measurements were conducted in 108 children aged between 3;6-11;11 years at the frequencies 0.5, 1, 2, 4 kHz (n = 82) and additionally at 0.25, 3, 6, 8 kHz (n = 26) using Sentiero (PATH medical). Different animals represented different frequencies (bear 500 Hz, elephant 1 kHz, etc.). Each animal was present in three variants: Neutral to start the sound presentation, happy/healthy and sad/sick for indicating the two conditions 'heard' and 'not heard'. Before measurement a story was told such that the child was instructed that healthy animals will make sounds and sick animals are not able to. The test procedure progress was visualized by a shelf, from which the current test animal was selected. The test was controlled by the child itself via touch screen. This includes sound presentation as well as input if the sound was heard (healthy animal) or not (sick animal). The examiner supervised the measurement and assisted the child with the entry when indicated. The examiner could also intervene in the measurement procedure at any time or do a retest at any frequency whenever necessary.

Additionally, hearing threshold estimation by means of DPOAE I/O functions (see Relation between DPOAEs and behavioural pure-tone thresholds p.69) were performed in 36 children from the collective. DPOAE I/O functions were recorded at

frequencies f2 = 1, 1.5, 2, 3, 4 and 6 kHz with primary tone levels (L2) in the range from 10 to 65 dB SPL and threshold were estimated by linear regression analysis. Primary tone levels L1 and L2 were set according to the "scissors paradigm". The frequency ratio f2/f1 was 1.2.

For comparison, play-audiometry pure tone thresholds were determined at the corresponding frequencies.

There was a highly significant ($p<0.001$) correlation between image-based (MAGIC) and play-audiometry (PTA) thresholds. The correlation coefficient (r) ($n=1247$) was 0.73. The histogram of the difference between image-based and play-audiometry thresholds showed normal distribution. Mean and standard deviation of the differences amounted to -1.5 dB and 9.6 dB, respectively. Test time per frequency (one ear) was on average about 30s, ranging from 14s to 91s. Test time decreased with increasing age.

8 PTA - Description of Methods

Pure-tone audiometry (PTA) is the testing of a person's ability to hear various sound frequencies. The test is performed with the use of an audiometer. Otoscopy should be done prior to PTA to determine if there are any blockages in the ear canal due to ear wax. Before the test, the subject has to be instructed about the task. As PTA is a psycho-acoustical test method the ability, willingness, and concentration of the subject to co-operate are essential. Also, placement of the transducers is important. Variation in earphone position up-down or front-back and leakage between earphone and ear may give rise to falsely poor hearing threshold levels, particularly at the highest frequencies.

Hearing is commonly measured at frequencies varying from low (250 Hz) to high sound frequencies (8 kHz). It should be emphasized that this is just a part of the entire human auditory range, which extends between 20 Hz and 20 kHz. The core method of PTA is to present a pure-tone close to threshold, and keep dropping the intensity in 10 dB steps until the person stops responding (raising their hand or pushing a button). Then the sound pressure level goes back up in 5 dB steps until the person starts responding again. This is conventionally done at 6 octaves at 250, 500, 1000, 2000, 4000, and 8000 Hz.

PTA starts by presenting sound via headphones (air conduction) or insert sound probes or free-field loudspeakers. When there is a hearing loss, the next step is to determine whether the loss is caused by a sensorineural hearing loss or an outer or middle ear problem. This distinction is made by bone conduction where the sound is transmitted to the ear through a bone vibrator placed on the mastoid bone behind the ear. In doing this the middle-ear is bypassed. If there is better hearing for bone conduction than for air conduction (air-bone gap) a conductive hearing loss is likely. If both air conduction and bone conduction thresholds are out of the normal range a sensorineural (cochlear or retro-cochlear impairment) is likely. To differentiate a detected sensorineural hearing loss supra-threshold testings

(Fowler, Carhart, loudness scaling etc.) have to be performed. OAEs and auditory brain-stem potentials are important tests for a topological diagnostic.

Bone conduction testing in persons with hearing loss must be done with masking the opposite ear to prevent sound from the stimulated side from going over to the good side (cross hearing). The threshold of the test ear is measured at the same time as presenting the masking noise to the non-test ear. Thus, thresholds obtained when masking has been applied, provide an accurate representation of the true hearing threshold level of the test ear. A reduction or loss of energy occurs with cross hearing. It varies from 40 dB to 80 dB with supra-aural headphones. However, with insert earphones it is in the region of 55 dB. The use of insert earphones reduces the need for masking.

The threshold is plotted across test frequencies on a graph (audiogram). In case of air conduction, the right ear is usually plotted in red, using an 'x' symbol, and the left in blue, using an “o” symbol. In case of bone conduction, the right ear is indicated by a “<” (unmasked) or “[” (masked) symbol, the left ear by a “>” (unmasked) or “]” symbol (unmasked). Hearing loss is described in words as follows:

- Normal hearing
< 25 dB HL (adults)
< 15 dB HL (children)
- Mild hearing loss = 25-40 dB HL
- Moderate hearing loss = 41-65 dB HL
- Severe hearing loss = 66-90 dB HL
- Profound hearing loss = 90+dB HL

In screening PTA, the test results show whether the hearing threshold levels are better, equal to, or worse than the screening level used. The test tone is delivered to the ear at frequencies and intensity levels that have been chosen for the screen. The subject passes the screening test according to predefined criteria, e.g. a pass occurs if all tones are heard in each ear. Screening at certain selected levels and frequencies is faster than measuring hearing threshold levels. When using screening PTA, the question is whether a person’s hearing ability is better or worse than a certain reference level. In order to perform screening quickly, a restricted number of frequencies are tested at predefined levels.

Calibration of the test environment (to meet ambient noise requirements), the equipment and the stimuli to ISO standards is needed before testing proceeds. PTA only measures thresholds, rather than other aspects of hearing.

9 OAE - Description of Methods

9.1 Types of OAEs

The discovery of otoacoustic emissions (OAEs) (Kemp, 1978) has produced a totally new tool for diagnosing cochlear function. OAEs are the by-product of the non-linear sound amplification process in the cochlea (Davis, 1983, Dallos, 1992). In sound-conductive hearing-loss, where both the stimulus and the response amplitude are reduced, OAEs are difficult to measure, even with a mild sound-conductive hearing-loss (Margolis, 2002). Along with tympanometry and auditory brain stem responses, OAEs can differentiate between middle-ear, cochlear, and neural disorders. OHCs are reported to be impaired by sound overexposure, ototoxic drugs (e.g., therapeutic antibiotics), infections (e.g., meningitis, mumps, materno-fetal infection), and anoxia (e.g., birth trauma), or to be partly missing in genetic hearing-loss. OHC impairment results in a loss of sensitivity and frequency selectivity of the hearing organ (Liberman and Dodds, 1984). OAEs, as a by-product of cochlear non-linear sound amplification, then appear with reduced amplitude or disappear (Mills and Rubel, 1994).

Spontaneous OAEs (SOAEs) appear without any sound stimulation at a few frequencies in a healthy cochlea and seem to be a direct consequence of the cellular force generation of outer hair cells (OHCs) (Zwicker and Schloth, 1984, Burns et al., 1998, Jülicher et al., 2003). SOAEs do not appear in each normally hearing subject and are present in about a half of the normally hearing population, with a distinctly higher prevalence in women than in men (Bilger et al., 1990, Penner et al., 1993, Penner and Zhang, 1997). SOAEs are therefore not suited for audiological diagnostics.

Evoked OAEs are generated by external sounds, either by transient (clicks and tone bursts) or stationary stimuli (tones). **Transiently evoked OAEs (TEOAEs),** elicited by clicks or tone-bursts**,** represent the sum of the pulse responses of OHCs

along the cochlea. TEOAEs already disappear at mild hearing losses and are therefore a suitable tool for newborn hearing screening which is a selection procedure for deciding whether further diagnostics are advised or not (Robinette and Glattke, 2002). **Distortion product OAEs (DPOAEs)** represent cubic distortions of OHCs when stimulated simultaneously by two tones $f1$ (lower frequency) and $f2$ (higher frequency). DPOAEs arise directly from the frequency-selective compressive nonlinearity of OHCs (Brownell et al., 1985, Kemp et al., 1986). The two tones interact in the cochlea close to the characteristic place of $f2$. Thus, DPOAEs can be applied as a probe for frequency-specific assessment of cochlear dysfunction at the $f2$ place. In humans the $2f1$-$f2$ distortion component yields the highest amplitude and is therefore primarily used in audiological diagnostics (Gorga et al., 2000a). DPOAEs are reported to be measurable at a cochlear hearing-loss of up to 40-50 dB HL, representing approximately the range of the cochlear amplifier (Davis, 1983, Ruggero et al., 1997). TEOAEs and DPOAEs are present in essentially every normally hearing subject.

Stimulus frequency OAEs (SFOAEs) are elicited by one continuous, low-level sinusoidal signal. Recording of SFOAEs is difficult because stimulus and response superimpose.

Whereas TEOAEs more qualitatively assess cochlear function, **DPOAEs** provide quantitative information about the range and operational characteristics of the cochlear amplifier (CA), i.e. sensitivity, compression, and frequency selectivity. There are several DPOAE measures which are used for assessing the functioning of the CA:

DPOAE-grams plot the DPOAE level Ldp as a function of $f2$ (the main DPOAE generation site) for a selected combination of the primary-tone levels $L1$ and $L2$. It should be emphasized that DPOAE-grams reflect CA sensitivity best when recorded at close-to threshold stimulus levels (Janssen et al., 1998, Kummer et al., 1998, Dorn et al., 2001). DPOAE-grams when recorded with narrow frequency spacing of $f2$ (DPOAE fine-structure) may give information about the fine-structure of the behavioral pure-tone threshold. However, due to the superposition of the second DPOAE source (He and Schmiedt, 1993, He and Schmiedt, 1996, He and Schmiedt, 1997, Shera and Guinan, 1999) the correlation between the two measures is not clear. In normal hearing (normal CA), DPOAE-grams are close to each other at high and more separated at low stimulus levels reflecting cochlear non-linear sound processing. In cochlear hearing-loss ears (impaired CA), DPOAE-grams are more separated even at high stimulus levels, revealing loss of CA compression (Janssen et al., 1998, Kummer et al., 1998, Neely et al., 2003).

DPOAE level I/O-functions plot the DPOAE level Ldp as a function of primary-tone level $L2$ for a selected $f2$ and thus reflect CA dynamics at the $f2$ place in the cochlea (Dorn et al., 2001). In normal hearing, in response to low-level stimuli, DPOAE level I/O-functions exhibit steep slopes, while at high stimulus

levels slopes decrease, thus mirroring the strong amplification at low and decreasing amplification (saturation) at moderate sound levels. However, this is only true when a stimulus setting (e.g. the "scissor" paradigm) is used which accounts for the different compression of the primary-tones at the *f*2 place (Kummer et al., 2000).

DPOAE pressure I/O-functions plot the DPOAE pressure *p*dp (instead of the DPOAE level *L*dp) as a function of the primary-tone level *L*2. Due to the logarithmic dependency of the DPOAE level on the primary-tone level there is a linear dependency between DPOAE pressure *p*dp and primary-tone level *L*2 (Boege and Janssen, 2002). Thus, DPOAE data can easily be fitted by linear regression analysis. The intersection point of the linear regression line with the *L*2-axis at *p*dp = 0 Pa can then serve as an estimate of the stimulus level at the DPOAE threshold, i.e., *L*dpth (Boege and Janssen, 2002, Gorga et al., 2003).

Estimated threshold level L_{dpth} when plotted across frequency f_2 provides a measure for estimating CA threshold at the f_2-place.

DPOAE slope, calculated from DPOAE level I/O-functions (e.g., between stimulus levels *L*2 of 40 and 60 dB SPL), indicates CA compression. When plotted across frequency, a slope profile can be established. In ears with cochlear hearing-loss, the slope *s* of the DPOAE level I/O-function increases with increasing hearing-loss indicating loss of CA compression (Janssen et al., 1998, Kummer et al., 1998, Müller and Janssen, 2004, Neely et al., 2003).

There are some **limitations** when using DPOAE measures for assessing peripheral sound processing. First, electric microphone noise, physiological noise (breathing, blood flow) and external acoustic noise do not allow OAE measurements at very low stimulus levels. Especially below 0.5 kHz, reliable OAE measurements are not possible even at high stimulus levels. Second, because of the limited frequency range of the sound probe's electro-acoustic transducers, high-frequency OAE measurements are difficult without using specialized devices. Third, standing waves in the outer ear canal make a defined stimulus setting difficult to obtain. Fourth, beside the main DPOAE source at *f*2, a secondary DPOAE source is present at the 2*f*1-*f*2 place, which interacts with the main source constructively or destructively at the *f*2 place (Whitehead et al., 1992, Brown et al., 1996, Shera and Guinan, 1999). Therefore, the DPOAE does not exactly reflect OHC function at the *f*2 place. When all these factors are considered, it is easy to see how OAE measures can be misinterpreted.

9.2 Clinical applications of TEOAEs/DPOAEs

30 years after the discovery of OAEs, OAE measurements are a standard part of the audiometric diagnostic test battery. OAEs are a means of acquiring non-inva-

sive information about disorders of an essential element of sound processing, i.e., the cochlear amplifier (CA), and hence allow assessment of loss of sensitivity, compression, and frequency-selectivity of the hearing organ. Like tympanometry, which examines the status of the middle-ear, OAEs are a fast and easy-to-handle method for examining cochlear function objectively. **OAEs extend the objective audiometric test battery.** They allow a direct examination of cochlear function. Subjective tests are only able to assess disorders of sound processing as a whole. Tympanometry, OAEs, and auditory brain stem responses (ABRs, ASSRs), in combination, allow for a differentiation between sound-conductive, cochlear, and neural hearing-loss. Minute changes in hearing capability are detectable by OAEs.

There are four **main OAE applications** in clinical diagnostics:

- Newborn hearing screening
- Confirmation of a cochlear hearing-loss along with tympanometry and auditory brain stem responses
- Quantitative evaluation of hearing-loss and recruitment for providing hearing aid fitting parameters
- Detecting beginning cochlear impairment during noise exposure or ototoxic drug administration

Newborn Hearing Screening is a selection procedure used to decide whether further diagnostics are advised or not (Wilson and Jungner, 1968). Consequently, a screening decision is binary: "pass" (negative finding, no diagnostics necessary), or "refer" (positive finding, follow-up diagnostics advised). The requirements for screening are different from those for diagnostics. Because screening is performed in large populations, the devices used typically provide automatic evaluation rather than rely on an expert's judgement.

A screening test should be performed as quickly as possible. Therefore, the respective methods must avoid long preparation times and the test should stop automatically if the desired quality of the result is achieved. TEOAE and DPOAE are widely regarded as being suitable for screening in newborns and infants, as they are not present in the case of outer hair cell (OHC) dysfunction (e.g. Kemp and Ryan, 1991, Gorga et al., 2000b, Norton et al., 2000b, Norton et al., 2000a). The premise for this approach is that inner ear hearing-loss always includes OHC damage or malfunction. Additionally, significant conductive losses due to **Eustachian tube dysfunction and/or amniotic fluid** in the tympanic cavity also cause "refer" results under screening conditions.

DPOAE newborn hearing screening is usually performed in the mid-frequency region (e.g. between 1.5 and 4 kHz). High-frequency testing is less reliable, due to the standing-wave problem and the limitation of the electro-acoustic transducer. Below 1 kHz, the SNR is insufficient, so that also low-frequency testing is inadvised. DPOAEs are elicited at different primary-tone levels, so that a multi-fre-

quency and multi-level test procedure is provided. Extrapolated DPOAE I/O-functions are used to estimate hearing thresholds (Boege and Janssen, 2002, Gorga et al., 2003).

A therapy for hearing disorder can be developed only after knowing which stage of the auditory pathway is impaired. Psychoacoustic tests are able to differentiate between sound-conductive and sensorineural hearing-loss by evaluating the difference between sound and bone-conductive pure-tone thresholds. The **discrimination of a sensorineural hearing-loss**, i.e., the differentiation between a sensory (cochlear) and a neural disorder with subjective testing is unreliable, because the validity of these tests (Short Increment Sensitivity Index (SISI), Fowler, Carhart) is limited. Moreover, in non-cooperative patients or infants, psychoacoustic tests can not be performed. In such cases, only objective tests help in achieving the goal of determining end organ integrity. Using tympanometry, OAEs, and ABRs/ASSRs, the site of the impairment in the auditory pathway can be ascertained with high reliability.

OAEs are used primarily as function detectors in clinical practice. As a general rule, if there is a suspicion of a hearing disorder, the measurement of OAEs should be used as the first audiological test. It is fast and helps to confirm normal middle-ear and cochlear function. This is the case if OAEs are present over a wide frequency range. If OAEs are absent, then middle-ear or cochlear (OHC) pathology is likely. OAEs then should be followed by tympanometry. If the tympanogram is normal and OAEs are absent, then a cochlear disorder is likely. If the tympanogram is abnormal, a sound-conductive hearing-loss is likely. If both the tympanogram and OAEs are normal, ABRs/ASSRs are needed to reveal whether there is a cochlear (inner hair cell) or neural pathology. For example, in auditory neuropathy, where synchronization of neural activity is malfunctioning (either due to inner hair cell synaptic or neural dysfunction), normal OAEs and abnormal ABRs occur (Doyle et al., 1998, Starr et al., 1996). OAEs are, of course, also a suitable means for testing individuals, who are only simulating a hearing-loss.

Especially for hearing-aid adjustment in infants, a **quantitative evaluation of the hearing-loss and recruitment** is necessary. When elicited by high stimulus levels (which is common in clinical practice), TEOAEs are absent at a cochlear hearing-loss exceeding 20 dB HL, whereas DPOAEs are absent only at a cochlear hearing-loss exceeding 40-50 dB HL. Thus, when using TEOAEs and DPOAEs elicited at high stimulus levels only, a rough estimate of the hearing-loss is possible. For example, when TEOAEs are absent and DPOAEs are present, then the hearing-loss is suggested to be not more than 30 dB HL.

In principle, both DPOAEs and TEOAEs allow acquisition of **frequency-specific information** about a hearing-loss problem. When stimulating the ear with a click or a tone-burst, almost all OHCs along the cochlear partition, or a part of them (the site in the cochlea depending on the carrier frequency of the tone-burst), are

excited. Due to frequency dispersion in the cochlea, a specific component of the TEOAE response can be directly traced to a specific frequency component of the transient signal. As the basilar membrane at basal sites moves faster than at more apical sites, high-frequency TEOAE components stem from basal cochlear sites, whereas low-frequency TEOAE components come from more apical ones. However, due to the fact that the stimulus and the high-frequency TEOAE components superimpose (and therefore have to be canceled during TEOAE recording), TEOAEs fail to measure cochlear function above 4 kHz. In contrast, DPOAEs have the advantage of being capable of superior detection of a high-frequency hearing-loss. This is due to the fact that stimulus (primary-tones at f2 and f1) and response (2f1-f2) do not superimpose. However, calibration errors due to standing waves in the outer-ear canal, can lead to misinterpretation of DPOAE results above 6 kHz.

The **relation between OAE level and auditory threshold** - or rather the lack of it – is strongly debated. Earlier, it was common to define confidence limits to determine the degree of certainty with which any measured response could be assigned to either normal or impaired hearing (Gorga et al., 1996, Gorga et al., 2000a), or to define a 'DPOAE detection threshold' as the stimulus level at which the response equalled the noise present in the instrument (Dorn et al., 2001). However, since the noise is of technical origin (e.g., microphone noise) the threshold evaluated in this way does not match the behavioural threshold. A more relevant measure is the intersection point between the **extrapolated DPOAE I/O-function** and the primary-tone level axis at which the response's sound pressure is zero and hence at which OHCs are inactive (Boege and Janssen, 2002, Gorga et al., 2003). A linear dependency between the DPOAE sound pressure and the primary-tone sound pressure level is present (Boege and Janssen, 2002) when using the "scissor" paradigm for eliciting DPOAEs (Kummer et al., 2000). Because of the linear dependency, DPOAE data can be easily fitted by linear regression analysis in a semi-logarithmic plot, where the intersection point of the regression line with the L2 primary-tone level axis at pdp = 0 Pa can thus serve as an estimate of the DPOAE threshold. The estimated DPOAE threshold Ldpth is independent of noise and seems to be more closely related to behavioural threshold than the DPOAE detection threshold (Boege and Janssen, 2002, Gorga et al., 2003).

When converting DPOAE sound pressure level (SPL) to hearing level (HL), the estimated DPOAE thresholds can be plotted in an audiogram form (DPOAE-audiogram). **DPOAE-audiograms** can be applied in babies with a refer result in newborn hearing screening to reveal a transitory sound-conductive hearing loss due to Eustachian tube dysfunction and/or amniotic fluid in the tympanic cavity or to confirm a persisting cochlear hearing loss in follow-up diagnostics. Test time for establishing a DPOAE-audiogram takes a couple of minutes. DPOAE-audiograms are an alternative method to behavioural audiometry or frequency-specific evoked response audiometry (tone burst auditory brain-stem responses (ABRs), auditory steady state responses (ASSRs) in case of mild and moderate hearing

loss. In contrast to TEOAE, common DPOAE elicited at high primary tone levels, and click-evoked ABR, which only qualitatively describe the hearing loss, DPOAE-audiograms are able to quantitatively assess the hearing loss at distinct frequencies. This is an essential advantage over tone burst ABR or ASSR. Predicting hearing loss at five frequencies by tone burst ABR or ASSR takes more than half an hour. Thus, DPOAE audiograms can serve as an advanced tool for **bridging the gap between screening and audiological testing** in pediatric audiology.

The objective of **hearing screening in childhood** is to identify hearing impairment which are not obvious or apparent and will cause significant disability or handicap for the child concerned. Late identification may compound problems in communication, language acquisition and affect other areas of development. Contrary to newborn hearing screening, **preschool hearing screening** tests should provide more frequency-specific and quantitative information on the hearing loss. Extrapolated DPOAE I/O-functions provide a frequency-specific and quantitative assessment of the hearing loss.

The **DPOAE growth rate** steepens when the auditory threshold is elevated (Janssen et al., 1998, Kummer et al., 1998, Boege and Janssen, 2002, Gorga et al., 2003, Neely et al., 2003) and differs significantly between hearing-loss classes (their width being 10 dB) (Janssen et al., 2005b). The slope of DPOAE I/O-functions is reported to be related to the slope of the loudness functions (Neely et al., 2003, Müller and Janssen, 2004). Thus, the slope of DPOAE I/O-functions is suggested to allow a quantitative assessment of CA compression and hence provide an **objective recruitment test**. Especially for hearing aid adjustment in children, a quantitative evaluation of the hearing loss and recruitment is necessary. With the help of the DPOAE audiogram and the DPOAE growth characteristic quantities of the cochlear impaired ear and hence additional parameters for a **non-cooperative hearing aid adjustment** can be provided (Müller and Janssen, 2004).

OAE measures are stable through time in any particular individual and hence are capable of **monitoring recovery from OHC impairment**. Therapeutic drugs such as antibiotic (e.g., aminoglycosides) and anti-tumor chemotherapeutic (e.g., cisplatin) agents are reported to induce an irreversible hearing-loss, that typically affects the highest frequencies first, with hearing-loss systematically progressing to the lower frequencies (e.g. Kopelman et al., 1988, Fausti et al., 1994, Berg et al., 1999, Stavroulaki et al., 2001). Early detection of **ototoxicity** is important for providing effective management options such as substitution of medications, change of dosage, and mode of administration (Lonsbury-Martin and Martin, 2001). Because TEOAEs are less effective above 4 kHz, DPOAEs are the test of first choice for detecting and monitoring OHC dysfunction due to ototoxic drugs. Moreover, DPOAEs have an additional advantage over TEOAEs, in that they can give information about compression of the OHC amplifiers. If OHC function is disturbed during the toxic process then not only DPOAE level, but also DPOAE

growth should be altered. Like anitibiotic and chemotherapeutic drugs, salicylate is also known to affect hearing sensitivity and to induce **tinnitus**. (Myers and Bernstein, 1965, McFadden and Plattsmier, 1984, Wier et al., 1988, Long and Tubis, 1988, Boettcher and Salvi, 1991, Brown et al., 1993, McFadden and Pasanen, 1994). However, most importantly, impairment due to salicylate toxicity is reversible. Assuming that a loss of OHC stiffness is responsible for distortions within cochlear micromechanics, the corresponding tonic change at the inner hair cell activity may be one potential correlate of tinnitus (Janssen et al., 2000).

Since **OAEs directly reflect OHC dysfunction**, they are therefore the method of choice in occupational medicine where the indisputable proof of a cochlear hearing-loss is required.

9.3 TEOAE/DPOAE recording

OAEs are low-level sound emissions that occur with sound pressure levels from a maximum amounting to about 20 dB SPL down to the limiting noise-floor level. Therefore, the recording of OAEs requires the use of a highly sensitive low-noise microphone. For DPOAE recording, separate loudspeakers are commonly used for each primary-tone in order to exclude technically generated distortion components. Both the **microphone** and the **loudspeakers** of the ear probe need to be miniaturized so that the ear probe is small enough to be placed inside the ear canal (Fehler: Referenz nicht gefunden). A tight fit of the probe is essential for OAE recording. If there is leakage between the ear-tip and ear canal, low frequency sound components cannot be recorded properly. Furthermore, the closure of the ear canal by the ear-tip excludes external sounds. In addition, it is essential to make sure that the ear canal is clean and that the ear probe ports are not blocked with ear canal wax. For clinical practice, it is important that ear probes are designed to offer easy access for cleaning ports or replacing clogged ear-tips.
To achieve low noise-floor levels, OAE measurements are conducted in a **sound-attenuating booth** or any other quiet environment. For bedside use portable measuring devices are used. Automated measuring and evaluation procedures guarantee test consistency and simplify the interpretation of OAE recordings.
Fourier transform (FFT) computations from the time-domain signal allows for automatic evaluation of OAE signals. To minimize the influence of unwanted external signals, algorithms for noise reduction and artefact rejection are applied. In addition, the noise-floor level is reduced by time domain averaging of the recorded signal. TEOAE response ‘sees’ almost the whole cochlea, whereas the DPOAE response reflects only a limited region of the cochlea. Therefore, **TEOAEs give a rapid overview of cochlear function**, whereas **DPOAEs provide more quantitative information about sound processing** at distinct cochlear places.

The noise-floor level is usually higher at low frequencies due to microphone properties and low-frequency body sounds such as breathing. **Artefact rejection** can be performed by elimination of high noise level buffers sensitive to, e.g., breathing, swallowing, or head movements of the subject. Furthermore, when recording TEOAEs, stimulus artefacts may generate signals being in phase in two averaging buffers resulting in a pseudo response of high reproducibility. By means of **windowing functions**, the stimulus artefact can be excluded so that the reproducibility of the overall signal is restricted to the signal section of interest (Kemp et al., 1990a, Kemp et al., 1990b). It should be emphasized that since the stimulus artefact always appears in the early recording period the high frequency TEOAE components get lost as a result of the windowing procedure.

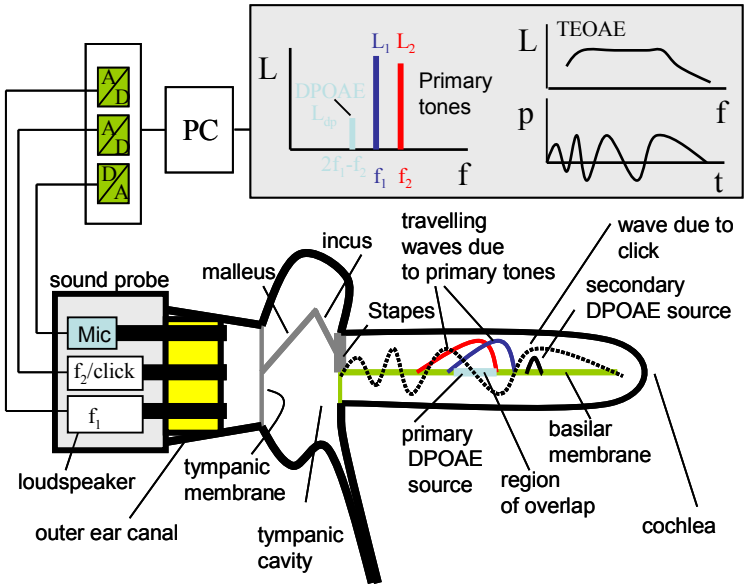


Fig. 9.1: Schematic drawing to show how TEOAEs and DPOAEs are evoked within the cochlea and subsequently measured in the outer ear canal. The sound probe consists of either one loudspeaker for applying a click stimulus (TEOAE) or of two loudspeakers for applying two independently generated primary-tones shown at top right with frequencies f_1 and f_2 and levels L_1 and L_2, and one microphone (Mic) for measuring the acoustic response signal. TEOAEs represent OHC pulse responses along the basilar membrane. Basal responses appear at the beginning, and apical responses at the end of the TEOAE time function. DPOAEs are generated within the region of overlap of the traveling waves of the two primary-tones close to the f_2 place. A/D = Analog-Digital-Converter, D/A = Digital-Analog-Converter, PC = Personal Computer, L = sound pressure level, p = sound pressure, f = frequency, t = time.

There are several objective methods for **separating the emission signal from the background noise** and for automatically evaluating the validity of a recorded emission. For TEOAEs mainly three signal evaluation approaches are used. The first method is based on the calculation of the **buffer correlation** of the time domain averaged signals between two separate signal buffers (Kemp et al., 1990a). If the two buffers are completely identical, the correlation coefficient is 1 and thus the reproducibility 100%. A signal is commonly accepted as valid for a reproducibility exceeding a minimum of 60%. The second method relies on the computation of the **spectral power ratio** of the sum and the difference of the two signal buffers. denoted as the signal-to-noise ratio (SNR). The pass criterion for a valid signal is typically set to an SNR of 6 dB. The third signal validation procedure is based on a binomial statistical test, which determines the statistical probability that an emission has been recorded. **Binomial statistics** reduces the recorded signal to binary events, and uses knowldge on the expected distribution of these events (binomial distribution) (Giebel, 2001).
In the case of DPOAEs, commercially available systems perform mainly two different data validation procedures. The first method is based on the calculation of the noise-floor level by averaging the levels of several adjoining frequency components around the DPOAE frequency component, with the **SNR** being indicated by the difference between the emission level and the noise-floor level. Here also, the SNR criterion is usually set to 6 dB. The second data validation procedure is based on a phase statistics method, which checks the coupling of the DPOAE component phase to the phase of the primary-tones. The **phase statistics** average normalized phase vectors of the signal received at the known DPOAE frequency. Like the binomial statistics, the vector sum can be scaled in probability terms, providing defined and very high sensitivities. A typical level of significance exceeds 99% per single frequency test.

9.4 TEOAE/DPOAE reproducibility

The inter-individual variance of the TEOAE level is high (standard deviation > 10 dB)(Kemp et al., 1986, Probst et al., 1987, Bonfils and Uziel, 1989, Smurzynski and Kim, 1992). The **intra-individual variance** of the DPOAE level is much smaller (standard deviation < 2 dB) (Johnsen and Elberling, 1982b, Johnsen and Elberling, 1982a, Harris et al., 1991). Recently, Janssen et al. (2005a) showed that repetitive DPOAE measurements with unchanged sound probe position exhibited an exponentially increasing standard deviation of DPOAE level with increasing SNR. For example, at a SNR of 10 dB, the standard deviation amounts to 1.8 dB, at a SNR of 20 dB to 0.7 dB, and at a SNR of 40 dB to 0.1 dB. This means that the higher the SNR, the higher is the reliability of the DPOAE measurement. This finding is important with respect to the evaluation of small DPOAE changes. For clinical practice, however, repetitive OAE measurements with **changed sound**

probe position are relevant. For example, the standard deviation when changing sound probe position amounted to about 1.6 dB (Müller et al., 2005).

DPOAEs are supposed to primarily reflect OHC activity at the f_2 place. However, there is evidence that DPOAEs are generated by **two distinct cochlear sources** (Whitehead et al., 1992, Brown et al., 1996, Shera and Guinan, 1999). As already mentioned, the first source, the effect of which is actually intended to be measured, is located at the region of overlap of the traveling waves of the two primary-tones near the *f*2 place and is due to intermodulation distortion. The second source, which is unintentionally adding to the first source emission, is located at the characteristic frequency place of the emission at 2*f*1-*f*2 and is due to reflection of energy that has travelled apically from the overlap region near *f*2. Thus, energy from both interacting sources yield the composite DPOAE signal which is actually recorded in the outer ear canal. The influence of the second DPOAE source may be observed when monitoring the DPOAE level across frequency with narrow frequency spacing of *f*2 (DPOAE fine-structure). Due to either destructive or constructive superposition of the two DPOAE sources across frequency, a number of investigators have described a pattern of dips and peaks in the DPOAE fine-structure in normal hearing subjects (He and Schmiedt, 1993, He and Schmiedt, 1996, He and Schmiedt, 1997, Talmadge et al., 1999). However, for clinical evaluation of DPOAE I/O functions, the interference of the **second DPOAE source** makes the interpretability and the accuracy of deduced measures, such as DPOAE threshold and compression, difficult. There have been attempts to minimize the influence of the second source by presenting an additional suppressor tone near 2*f*1-*f*2 (Heitmann et al., 1998), or by using a time-windowing procedure, which is able to separate the two sources (Mauermann and Kollmeier, 2004).

The measured OAE presssure in the outer ear canal depends on the ear canal volume. Because of the smaller ear canal volume, OAE pressure in newborns is higher compared to that of adults (Norton, 1992, Lasky, 1998b, Lasky, 1998a, Abdala, 2000). As a consequence, OAEs in newborns are easier to measure.

9.5 TEOAE/DPOAE stimulus setting

TEOAE responses can be evoked by two types of stimulus trains: (i) by a set of four clicks of equal magnitude (referred to as the linear protocol) or (ii) by three clicks of positive polarity followed by a fourth click of an inverse polarity with a relative magnitude of 9.5 dB higher than the corresponding positive clicks (referred to as the **non-linear protocol**) (Kemp et al., 1986, Bray, 1989). Under the hypothesis that the TEOAE recordings originate from saturated cochlear generators, it is assumed that the non-linear protocol removes stimulus artifacts of a linear nature, i.e., the stimulus itself, because sound signals increase linearly with

the stimulus level, while sound signals increasing non-linearly with the stimulus level, i.e., the emission emerging from the non-linear operation of OHCs, remain. It is generally accepted that the non-linear protocol is a practical compromise to maximize the reliability of a TEOAE recording (Kemp et al., 1990a, Kemp et al., 1990b, Grandori and Ravazzani, 1993, Von Specht et al., 2001, Hatzopoulos et al., 2003).

When using the "scissor" primary-tone setting (Fig. 9.2), which accounts for the different compression of the primary-tone traveling waves at the *f*2 place (Whitehead et al., 1995c, Whitehead et al., 1995a, Kummer et al., 2000, Boege and Janssen, 2002), the **DPOAE I/O-function reflects compressive non-linear sound processing** known from direct measurements of basilar membrane displacements (Ruggero et al., 1997). Due to the steep slope of the traveling wave towards the cochlear apex, the maximum interaction site is close to the *f*2 place in the cochlea. Thus, OHCs at the *f*2 place contribute most to DPOAE generation. The number of OHCs contributing to DPOAE generation depends on the size of the overlapping region, which is determined by the primary-tone levels *L*1 and *L*2, respectively, and the frequency ratio *f*2/*f*1 of the primary-tones *f*1 und *f*2. To preserve optimum overlap of the primary-tone traveling waves at a constant frequency ratio $f_2/f_1=1.2$, the primary-tone level difference has to be increased with decreasing stimulus level resulting in a *L*1|*L*2 setting described by *L*1=0.4*L*2+39. This **"scissor" $L_1|L_2$ setting** (L1=65|L2=65, L1=63|L2=60, L1=61|L2=55 L1=59|L2=50, L1=57|L2=45, L1=55|L2=40, L1=53|L2=35, L1=51|L2=30 L1=49|L2=25, L1=47|L2=20) was derived from findings on the influence of the *L*1|*L*2 setting on the DPOAE level *L*dp (Kummer et al., 2000). It should be emphasized that it is not the *L*1=*L*2 setting, but the "scissor" *L*1|*L*2 setting which yields compressive DPOAE growth reflecting non-linear CA sound processing (Fig. 9.3).

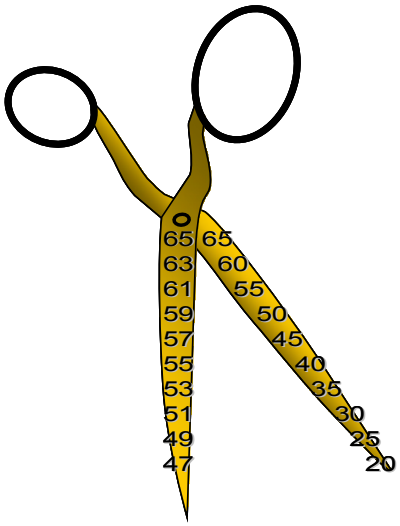


Fig. 9.2: Scissor-paradigm L1=0.4L2+39 for yielding best overlap of the primary tone travelling waves.

9.6 TEOAE/DPOAE stimulus calibration

Stimulus calibration is important to ensure proper data interpretation and comparability. There is a serious problem with stimulus calibration since, due to **standing waves in the ear canal**, the sound pressure level at the ear drum cannot be accurately set from measurements at the tip of the sound probe.

The most commonly used calibration method is the in-the-ear calibration based on the measurement of the sound pressure level at the ear probe microphone for constant voltage at the loudspeaker (Whitehead et al., 1995b). However, the ear probe microphone is located in the outer ear canal while the relevant magnitude for the generation of OAEs is the actual sound pressure level at the eardrum. Thus, dependent on ear canal length and middle-ear impedance, there is a frequency-dependent deviance of unknown quantity between the nominal sound pressure level at the tip of the ear probe and the actual sound pressure level at the eardrum due to standing wave effects (Siegel, 1994). This deviation is usually highest at frequencies corresponding to $d = \lambda/4$ and $\lambda/2$ (d: distance between ear probe and eardrum). Thus, problems become serious around 3 kHz and above 6 kHz in adults, but are less important in newborns and infants due to the smaller ear canal length (Keefe et al., 1993). **Calibration errors** may cause a change in the shape and thus the compression of DPOAE I/O functions. Further improvement of ear probe calibration is therefore necessary to enhance the accuracy of clinically relevant measures deduced from DPOAE recordings such as, for example, estimated CA threshold and compression.

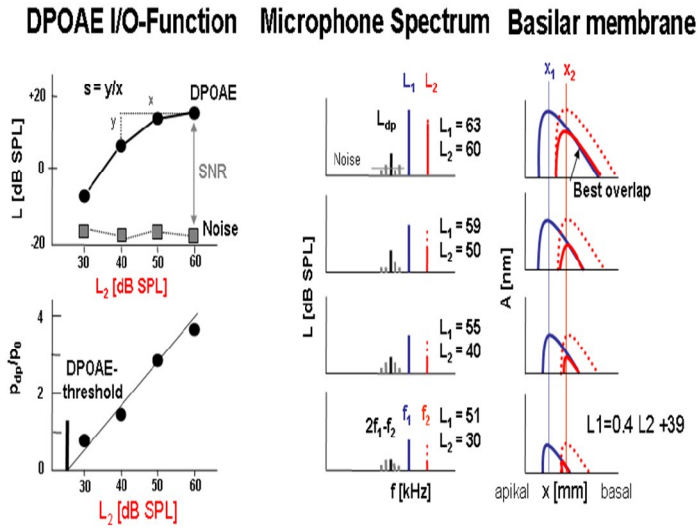


Fig. 9.3 Schematic drawing of how to evoke DPOAEs in a way that DPOAEs are able to reflect compressive cochlear sound amplification. For yielding best overlap of the travelling wave envelopes, primary tone levels L1 (blue) and L2 (red) have to be set according to the scissor paradigm L1=0.4 l2 + 39 (solid lines). For comparison, travelling wave envelopes are shown for L1=L2 condition (dotted lines). The L1 and L2 spectral lines are shown for the scissor paradigm solid line) and the L_1=L_2 paradigm (dotted line). DPOAEs (same data) are plotted in a double-logarithmic (L across L2) and semi-logarithmic scale (p across L2). Intersection of the linear regression line with L2 axis serves as an estimate of DPOAE threshold level.

In testing TEOAEs, calibration errors have less impact, because the wide-band stimulus is not influenced that strongly by standing wave problems. Apart from this, TEOAEs are usually stimulated with a click level that is relatively high, i.e., where cochlear compression already saturates cochlear motion. As opposed to DPOAEs, no level ratio between primary-tones needs to be fulfilled. This results in TEOAEs being less susceptible to stimulus calibration errors.

9.7 Relation between DPOAEs and behavioural pure-tone thresholds

The relation between DPOAE level and behavioural pure-tone threshold - or rather the lack of it – is strongly debated. Earlier, it was common to define confidence limits to determine the degree of certainty with which any measured response could be assigned to either normal or impaired hearing (Gorga et al., 1996, Gorga et al., 2000a), or to define a ‘DPOAE detection threshold’ as the stimulus level at

which the response equalled the noise present in the instrument (Dorn et al., 2001).

However, since the noise is of technical origin (e.g., microphone noise) the threshold evaluated in this way does not match the behavioural threshold. A more relevant measure is the intersection point between the extrapolated DPOAE I/O-function and the primary-tone level axis at which the response's sound pressure is zero and hence at which outer hair cell amplifiers are inactive (Boege and Janssen, 2002, Gorga et al., 2003). A linear dependency between the DPOAE sound pressure and the primary-tone sound pressure level is present (Boege and Janssen, 2002) when using the "scissor" paradigm for eliciting DPOAEs (Kummer et al., 2000). Because of the linear dependency, DPOAE data can be easily fitted by linear regression analysis in a semi-logarithmic plot, where the intersection point of the regression line with the $L2$ primary-tone level axis at $p\mathrm{dp} = 0$ Pa can thus serve as an estimate of the DPOAE threshold. The estimated DPOAE threshold $L\mathrm{dpth}$ is independent of noise and seems to be more closely related to behavioural threshold than the DPOAE detection threshold (Boege and Janssen, 2002, Gorga et al., 2003, Janssen et al., 2006).

Extrapolated DPOAE I/O-functions are used to determine DPOAE thresholds which can be displayed on in an audiogram form (DPOAE-audiogram). Circle symbol means threshold estimation by means of extrapolated DPOAE I/O functions, square symbol means simplified estimation where less than three valid responses are present and the lowest primary tone level – 15 dB is the estimate, arrow symbol means no DPOAE are measurable and thus the hearing loss is higher than 50 dB HL (Fig. 9.4).

Otoacoustic emissions (TEOAE and DPOAE) are widely regarded as being suitable for screening in newborns and infants, as they are not present in the case of outer hair cell dysfunction. (e.g. Kemp and Ryan, 1991, Gorga et al., 2000b, Norton et al., 2000b, Norton et al., 2000a). The premise for this approach is that inner ear hearing-loss always includes OHC damage or malfunction. However, conductive losses also cause "refer" results under screening conditions, mainly due to the attenuation of an existing OAE signal.

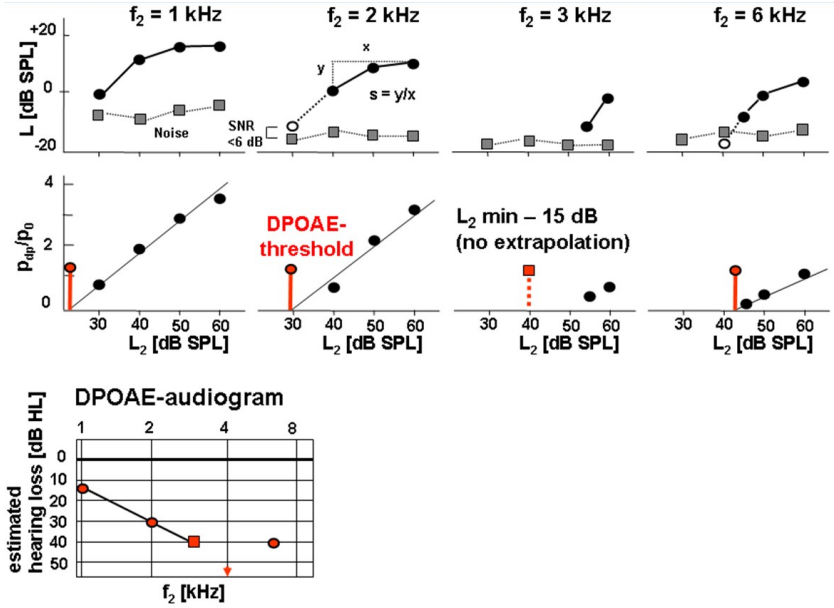


Fig. 9.4: Schematic drawing of how to determine DPOAE thresholds and to estimate hearing loss at different test frequencies (f2) (DPOAE-audiogram). DPOAEs are plotted in double-logarithmic (L across L2) and semi-logarithmic (p across L2) scales. Intersection of the linear regression line with L2 axis serves as an estimate of the DPOAE threshold level. At test frequencies where DPOAEs are only present at two L2 levels or one L2 level no extrapolation is done. In this case the estimated threshold is calculated by the lowest L2 (L2min) at which a valid DPOAE could be achieved minus 15 dB. After converting SPL in HL a DPOAE-audiogram is constructed. Circle means threshold estimation by means of extrapolated DPOAE I/O functions, square symbol means simplified estimation L2min – 15dB, arrow symbol means no DPOAE are measurable and thus the hearing loss is estimated to be higher than 50 dB HL.

A major disadvantage of using OAEs in screening protocols is a lower validity as compared to ABR methods (Norton et al., 2000b, Barker et al., 2000). This is especially true in populations with a high prevalence of slight threshold elevation due to a temporary sound-conductive hearing loss, as it is found in term neonates in the first 36 hours of life because of Eustachian tube dysfunction or amniotic fluid in the

tympanic cavity or due to a persisting sensory hearing-loss in premature and neonatal intensive care unit infants. In order to maintain a high sensitivity, the specificity may be reduced dramatically, making a screening procedure inefficient. To avoid high referral rates, OAE referrals should be followed up with an ABR screening before diagnostic assessment, i.e., two-stage screening (Rhodes et al., 1999, Norton et al., 2000a). DPOAE-audiograms may be an alternative means for revealing a temporary hearing loss in the early postnatal period caused by a temporary sound conductive hearing loss due to amniotic fluid or Eustachian tube dysfunction. When applying DPOAE audiograms before ABR screening, time and

costs can be saved in those babies where DPOAEs are measurable and thus no additional ABR is needed.

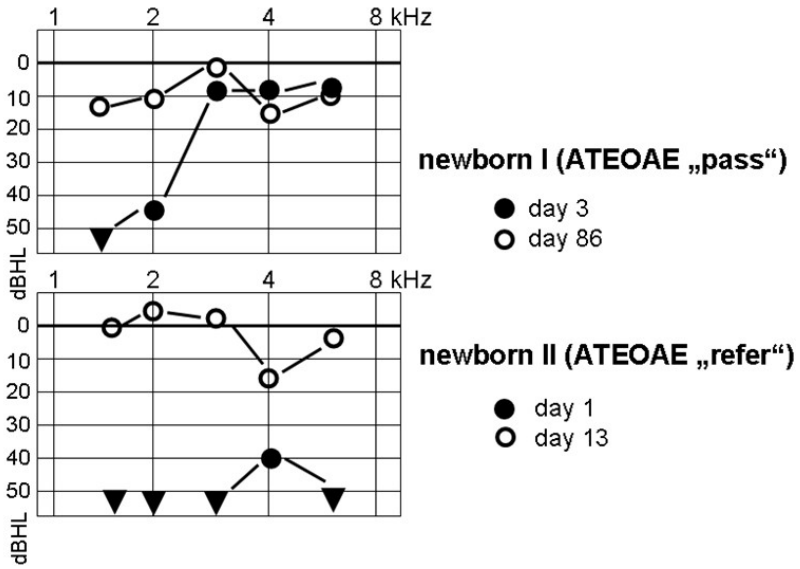


Fig. 9.5: DPOAE-audiograms in two newborns with temporary sound-conducted hearing loss.. Newborn I with a "pass" ATEOAE screening response exhibited a low-frequency hearing loss in the first measurement (3 days after birth). In the second measurement (86 days after birth) the DPOAE-audiogram indicated normal hearing. In newborn II with a "refer" ATEOAE screening response no DPOAE could be measured (except at 4 kHz) in the first measurement (1 day after birth). DPOAE-audiogram obtained in the second measurement (13 days after birth) indicated normal hearing.

Two case examples shall illustrate how DPOAE-audiograms can reveal temporary sound-conductive disorders in the early postnatal period (Fehler: Referenz nicht gefunden). In a 3 days old neonate with a "pass" response after ATEOAE screening the DPOAE-audiogram indicated a low frequency hearing loss. The DPOAE-audogram 83 days later revealed normal hearing function. In this baby, Eustachian tube dysfunction could have been the cause for the hearing loss within the first days of life where middle ear stiffness is increased and therefore low frequencies are affected. In another newborn with a "refer" ATEOAE screening response the DPOAE-audio

gram indicated a hearing loss of more than 50 dB at 1.5, 2, 3, and 6 kHz (arrows) and a 40 dB hearing loss at 4 kHz. The second measurement 12 days later revealed normal hearing function. In this baby, both a low- and a high-frequency sound-conductive hearing loss might have been present where middle-ear stiffness is increased due to Eustachian tube dysfunction and thus low frequencies are affected and middle-ear mass is increased due to amniotic fluid and thus high frequencies are affected.

Fig. 9.6 d shows mean and standard deviation of estimated DPOAE thresholds measured in 100 left and 100 right ears from 100 newborns at neonatal care unit. Mean age was 2.5 days. There was no significant difference between left and right ears. Standard deviation is partly due to different sound-conductive conditions during the early postnatal period. Results indicate that DPOAE threshold measurements can be done under hearing screening conditions.

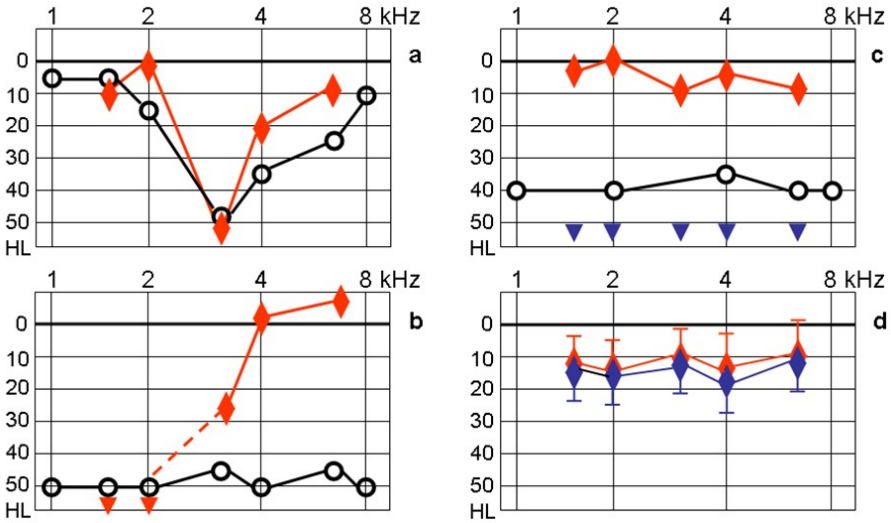


Fig. 9.6: Pure-tone audiograms (black symbols) and DPOAE-audiograms in 3 children - 6 years old, right ear (a), 5 months old, right ear (b), 3 months old, right (red) and left ear (blue) (c). Mean and standard deviation of estimated DPOAE thresholds (DPOAE-audiograms) of left (blue) and right ears (red) obtained in 100 newborns (d).

DPOAE-audiograms can be applied in newborns to reveal a temporary sound-conductive hearing loss or to detect a persisting cochlear hearing loss. In follw-up diagnostics, DPOAE-audiograms can serve as an advanced tool for bridging the gap between screening and audiological testing.

DPOAE-audiograms are useful in pediatric audiology since they provide frequency specific information about the hearing loss in a couple of minutes. Thus, they have an advantage over TEOAEs or click-evoked ABRs (because they can not quantitatively assess cochlear hearing thresholds at distinct test frequencies) and ASSRs (because their measuring time is extremely long).

Three case examples shall demonstrate the efficacy of DPOAE-audiograms in pediatric audiology (Fig. 8.6 a,b,c). In a 6 years old boy, pure-tone audiogram and DPOAE-audiogram exhibited a close correspondence (Fig. 8.6 a). However, in the younger children there was a high discrepancy between the behavioural free-field audiograms and the DPOAE-audiograms. The free-field audiogram of a 5 month old girl (Fehler: Referenz nicht gefunden b) indicated a hearing loss of 50 dB HL in the entire frequency range. However, the DPOAE-audiogram revealed a hearing loss only in the mid and low frequency region. Fehler: Referenz nicht gefunden c

shows the free-field audiogram and the DPOAE-audiograms of the left and the right ear. The free-field audiogram indicated a hearing loss of 40 dB HL. In the left ear no DPOAEs were measurable indicating that the hearing loss must be higher than 50 dB (arrows in Fehler: Referenz nicht gefunden c). In the right ear the DPOAE-audiogram revealed normal hearing.

DPOAE-audiograms may assess cochlear hearing loss more precisely than behavioural tests, especially in infants where the conditioned free-field audiogram does not reflect the real threshold. Moreover, unilateral hearing loss can be detected. DPOAE-audiograms are an automated measuring procedure with simple handling and short measuring time. No sedative is necessary in most cases. It should be emphasized that DPOAEs only reflect outer hair cell functionality and therefore are not present at a hearing loss higher 50 dB HL. However, the incidence of a hearing loss higher than 50 dB is low. Thus, in most of the children DPOAE are measurable. In cases where DPOAEs are not measurable ABRs or ASSRs have to be applied.

10 SUN - Description of Methods

SUN is a novel self-controlled speech in noise test designed for screening adults and older adults for hearing disability using a set of intervocalic consonants (VCVs) (see Paglialonga A., Tognola G., Grandori F. 2011. SUN test (Speech Understanding in Noise): a method for hearing disability screening. Audiology Research 1:e13). The test aims at logatome recognition, specifically at the identification of consonants and hence at the early assessment of age-related hearing loss. The test is fully automated using a three-alternative forced choice procedure in which three alternative VCVs (e.g., aFa, aGa, aSa) from a set of 12 items are displayed on a touch screen. VCVs are presented via headphones at different signal-to-noise ratios. Test person has to select the correct item from the screen. The test gives a tri-modal outcome: hearing ability within normal range (score $\geq$ 9/12), hearing ability might be below the normal range (score equal to 7 or 8), hearing ability well below the normal range $\leq$6/12).

Otoscopy should be done prior to the test to determine if there are any blockages in the ear canal due to ear wax. Before the test, the subject has to be instructed about the task. As SUN is a psycho-acoustical test method the ability, willingness, and concentration of the subject to co-operate are essential. Also, proper placement of the transducers and low ambient noise conditions are important for a reliable outcome.

Preliminary findings of a study on more than 1000 subjects suggests SUN to be suited for adult hearing screening because test time is short (2 minutes on average), cognitive load is low, and acceptability of test persons is high (see Paglialonga et al. 2011).

11 References

ABDALA, C. 2000. Distortion product otoacoustic emission (2f1-f2) amplitude growth in human adults and neonates. *J Acoust Soc Am,* 107**,** 446-56.

BARKER, S. E., LESPERANCE, M. M. & KILENY, P. R. 2000. Outcome of newborn hearing screening by ABR compared with four different DPOAE pass criteria. *Am J Audiol,* 9**,** 142-8.

BERG, A. L., SPITZER, J. B. & GARVIN, J. H., JR. 1999. Ototoxic impact of cisplatin in pediatric oncology patients. *Laryngoscope,* 109**,** 1806-14.

BILGER, R. C., MATTHIES, M. L., HAMMEL, D. R. & DEMOREST, M. E. 1990. Genetic implications of gender differences in the prevalence of spontaneous otoacoustic emissions. *J Speech Hear Res,* 33**,** 418-32.

BOEGE, P. & JANSSEN, T. 2002. Pure-tone threshold estimation from extrapolated distortion product otoacoustic emission I/O-functions in normal and cochlear hearing loss ears. *The Journal of the Acoustical Society of America,* 111**,** 1810-1818.

BOETTCHER, F. A. & SALVI, R. J. 1991. Salicylate ototoxicity: review and synthesis. *Am J Otolaryngol,* 12**,** 33-47.

BONFILS, P. & UZIEL, A. 1989. Clinical applications of evoked acoustic emissions: results in normally hearing and hearing-impaired subjects. *Ann Otol Rhinol Laryngol,* 98**,** 326-31.

BRAY, P. 1989. Click evoked otoacoustic emissions and the development of a clinical otoacoustic hearing test instrument. *Dissertation at the University College and Middlesex School of Medicine, London*.

BROWN, A. M., HARRIS, F. P. & BEVERIDGE, H. A. 1996. Two sources of acoustic distortion products from the human cochlea. *J Acoust Soc Am,* 100**,** 3260-7.

BROWN, A. M., WILLIAMS, D. M. & GASKILL, S. A. 1993. The effect of aspirin on cochlear mechanical tuning. *J Acoust Soc Am,* 93**,** 3298-307.

BROWNELL, W. E., BADER, C. R., BERTRAND, D. & DE RIBAUPIERRE, Y. 1985. Evoked mechanical responses of isolated cochlear outer hair cells. *Science,* 227**,** 194-6.

BURNS, E. M., KEEFE, D. H. & LING, R. 1998. Energy reflectance in the ear canal can exceed unity near spontaneous otoacoustic emission frequencies. *J Acoust Soc Am,* 103**,** 462-74.

DALLOS, P. 1992. The active cochlea. *J Neurosci,* 12**,** 4575-85.

DAVIS, H. 1983. An active process in cochlear mechanics. *Hear Res,* 9**,** 79-90.

DORN, P. A., KONRAD-MARTIN, D., NEELY, S. T., KEEFE, D. H., CYR, E. & GORGA, M. P. 2001. Distortion product otoacoustic emission input/output functions in normal-hearing and hearing-impaired human ears. *The Journal of the Acoustical Society of America,* 110**,** 3119-3131.

DOYLE, K. J., FUJIKAWA, S., ROGERS, P. & NEWMAN, E. 1998. Comparison of newborn hearing screening by transient otoacoustic emissions and auditory brainstem response using ALGO-2. *Int J Pediatr Otorhinolaryngol,* 43**,** 207-11.

FAUSTI, S. A., LARSON, V. D., NOFFSINGER, D., WILSON, R. H., PHILLIPS, D. S. & FOWLER, C. G. 1994. High-frequency audiometric monitoring strategies for early detection of ototoxicity. *Ear Hear,* 15**,** 232-9.

GIEBEL, A. 2001. Applying signal statistical analysis to TEOAE measurements. *Scand Audiol Suppl***,** 130-2.

GORGA, M. P., NEELY, S. T., DORN, P. A. & HOOVER, B. M. 2003. Further efforts to predict pure-tone thresholds from distortion product otoacoustic emission input/output functions. *J Acoust Soc Am,* 113**,** 3275-84.

GORGA, M. P., NELSON, K., DAVIS, T., DORN, P. A. & NEELY, S. T. 2000a. Distortion product otoacoustic emission test performance when both 2f1-f2 and 2f2-f1 are used to predict auditory status. *J Acoust Soc Am,* 107**,** 2128-35.

GORGA, M. P., NORTON, S. J., SININGER, Y. S., CONE-WESSON, B., FOLSOM, R. C., VOHR, B. R., WIDEN, J. E. & NEELY, S. T. 2000b. Identification of

neonatal hearing impairment: distortion product otoacoustic emissions during the perinatal period. *Ear Hear,* 21**,** 400-24.

GORGA, M. P., STOVER, L., NEELY, S. T. & MONTOYA, D. 1996. The use of cumulative distributions to determine critical values and levels of confidence for clinical distortion product otoacoustic emission measurements. *J Acoust Soc Am,* 100**,** 968-77.

GRANDORI, F. & RAVAZZANI, P. 1993. Non-linearities of click-evoked otoacoustic emissions and the derived non-linear technique. *Br J Audiol,* 27**,** 97-102.

GRANDORI, F., TOGNOLA, G. & ALESSIA, P. A speech-in-noise test for screening hearing ability in adults: the Speech Understanding in Noise (SUN) test. *Auris Nasus Larynx,* submitted.

HARRIS, F. P., PROBST, R. & WENGER, R. 1991. Repeatability of transiently evoked otoacoustic emissions in normally hearing humans. *Audiology,* 30**,** 135-41.

HATZOPOULOS, S., PETRUCELLI, J., MORLET, T. & MARTINI, A. 2003.

TEOAE recording protocols revised: data from adult subjects. *Int J Audiol,* 42**,** 339-47.

HE, N. & SCHMIEDT, R. A. 1997. Fine structure of the 2 f1-f2 acoustic distortion products: effects of primary level and frequency ratios. *J Acoust Soc Am,* 101**,** 3554-65.

HE, N. J. & SCHMIEDT, R. A. 1993. Fine structure of the 2f1-f2 acoustic distortion product: changes with primary level. *J Acoust Soc Am,* 94**,** 2659-69.

HE, N. J. & SCHMIEDT, R. A. 1996. Effects of aging on the fine structure of the 2f1-f2 acoustic distortion product. *J Acoust Soc Am,* 99**,** 1002-15.

HEITMANN, J., WALDMANN, B., SCHNITZLER, H.-U., PLINKERT, P. K. & ZENNER, H.-P. 1998. Suppression of distortion product otoacoustic emissions (DPOAE) near 2f[sub 1] - f[sub 2] removes DP-gram fine structure -- Evidence for a secondary generator. *The Journal of the Acoustical Society of America,* 103**,** 1527-1531.

JANSSEN, T., BOEGE, P., MIKUSCH-BUCHBERG, J. & RACZEK, J. 2005a. Investigation of potential effects of cellular phones on human auditory function by means of distortion product otoacoustic emissions. *The Journal of the Acoustical Society of America,* 117**,** 1241-1247.

JANSSEN, T., BOEGE, P., OESTREICHER, E. & ARNOLD, W. 2000. Tinnitus and 2f1-f2 distortion product otoacoustic emissions following salicylate overdose. *J Acoust Soc Am,* 107**,** 1790-2.

JANSSEN, T., GEHR, D. D., KLEIN, A. & MÜLLER, J. 2005b. Distortion product otoacoustic emissions for hearing threshold estimation and differentiation between middle-ear and cochlear disorders in neonates. *J Acoust Soc Am,* 117**,** 2969-79.

JANSSEN, T., KUMMER, P. & ARNOLD, W. 1998. Growth behavior of the 2 f1-f2 distortion product otoacoustic emission in tinnitus. *J Acoust Soc Am,* 103**,** 3418-30.

JANSSEN, T., NIEDERMEYER, H. P. & ARNOLD, W. 2006. Diagnostics of the cochlear amplifier by means of distortion product otoacoustic emissions. *ORL J Otorhinolaryngol Relat Spec,* 68**,** 334-9.

JOHNSEN, N. J. & ELBERLING, C. 1982a. Evoked acoustic emissions from the human ear. I. Equipment and response parameters. *Scand Audiol,* 11**,** 3-12.

JOHNSEN, N. J. & ELBERLING, C. 1982b. Evoked acoustic emissions from the human ear. II. Normative data in young adults and influence of posture. *Scand Audiol,* 11**,** 69-77.

JÜLICHER, F., CAMALET, S., PROST, J. & DUKE, T. A. J. 2003. Active amplification by critical oscillations. *In:* GUMMER, A. (ed.) *Biophysics of the Cochlea: from Molecule to Models.* New Jersey: World Scientific.

KEEFE, D. H., BULEN, J. C., AREHART, K. H. & BURNS, E. M. 1993. Ear-canal impedance and reflection coefficient in human infants and adults. *J Acoust Soc Am,* 94**,** 2617-38.

KEMP, D. T. 1978. Stimulated acoustic emissions from within the human auditory system. *J Acoust Soc Am,* 64**,** 1386-91.

KEMP, D. T., BRAY, P., ALEXANDER, L. & BROWN, A. M. 1986. Acoustic emission cochleography--practical aspects. *Scand Audiol Suppl,* 25**,** 71-95.

KEMP, D. T. & RYAN, S. 1991. Otoacoustic emission tests in neonatal screening programmes. *Acta Otolaryngol Suppl,* 482**,** 73-84.

KEMP, D. T., RYAN, S. & BRAY, P. 1990a. A guide to the effective use of otoacoustic emissions. *Ear Hear,* 11**,** 93-105.

KEMP, D. T., RYAN, S. & BRAY, P. 1990b. Otoacoustic emission analysis and interpretation for clinical purposes. *In:* GRANDORI, F., CIAFRONE, G. & KEMP, D. (eds.) *Cochlear mechanisms and otoacoustic emissions.* Karger.

KOPELMAN, J., BUDNICK, A. S., SESSIONS, R. B., KRAMER, M. B. & WONG, G. Y. 1988. Ototoxicity of high-dose cisplatin by bolus administration in patients with advanced cancers and normal hearing. *Laryngoscope,* 98**,** 858-64.

KUMMER, P., JANSSEN, T. & ARNOLD, W. 1998. The level and growth behavior of the 2 f1-f2 distortion product otoacoustic emission and its relationship to auditory sensitivity in normal hearing and cochlear hearing loss. *Journal of the Acoustical Society of America,* 103**,** 3431-3444.

KUMMER, P., JANSSEN, T., HULIN, P. & ARNOLD, W. 2000. Optimal L(1)-L(2) primary tone level separation remains independent of test frequency in humans. *Hear Res,* 146**,** 47-56.

LASKY, R. E. 1998a. Distortion product otoacoustic emissions in human newborns and adults. I. Frequency effects. *J Acoust Soc Am,* 103**,** 981-91.

LASKY, R. E. 1998b. Distortion product otoacoustic emissions in human newborns and adults. II. Level effects. *J Acoust Soc Am,* 103**,** 992-1000.

LIBERMAN, M. C. & DODDS, L. W. 1984. Single-neuron labeling and chronic cochlear pathology. III. Stereocilia damage and alterations of threshold tuning curves. *Hear Res,* 16**,** 55-74.

LONG, G. R. & TUBIS, A. 1988. Modification of spontaneous and evoked otoacoustic emissions and associated psychoacoustic microstructure by aspirin consumption. *J Acoust Soc Am,* 84**,** 1343-53.

LONSBURY-MARTIN, B. L. & MARTIN, G. K. 2001. Evoked Otoacoustic Emissions as Objective Screeners for Ototoxicity. *Semin Hear,* 22**,** 377,392.

MARGOLIS, R. H. 2002. Influence of middle-ear disease on otoacoustic emissions. *In:* ROBINETTE, M. S. & GLATTKE, T. J. (eds.) *Otoacoustic emissions: clinical applications.* 2. ed. ed. New York: Thieme.

MAUERMANN, M. & KOLLMEIER, B. 2004. Distortion product otoacoustic emission (DPOAE) input/output functions and the influence of the second DPOAE source. *J Acoust Soc Am,* 116**,** 2199-212.

MCFADDEN, D. & PASANEN, E. G. 1994. Otoacoustic emissions and quinine sulfate. *J Acoust Soc Am,* 95**,** 3460-74.

MCFADDEN, D. & PLATTSMIER, H. S. 1984. Aspirin abolishes spontaneous oto-acoustic emissions. *J Acoust Soc Am,* 76**,** 443-8.

MILLS, D. M. & RUBEL, E. W. 1994. Variation of distortion product otoacoustic emissions with furosemide injection. *Hear Res,* 77**,** 183-99.

MÜLLER, J. & JANSSEN, T. 2004. Similarity in loudness and distortion product otoacoustic emission input/output functions: implications for an objective hearing aid adjustment. *J Acoust Soc Am,* 115**,** 3081-91.

MÜLLER, J., JANSSEN, T., HEPPELMANN, G. & WAGNER, W. 2005. Evidence for a bipolar change in distortion product otoacoustic emissions during contralateral acoustic stimulation in humans. *J Acoust Soc Am,* 118**,** 3747-56.

MYERS, E. N. & BERNSTEIN, J. M. 1965. Salicylate ototoxicity; a clinical and experimental study. *Arch Otolaryngol,* 82**,** 483-93.

NEELY, S. T., GORGA, M. P. & DORN, P. A. 2003. Cochlear compression estimates from measurements of distortion-product otoacoustic emissions. *J Acoust Soc Am,* 114**,** 1499-507.

NORTON, S. J. 1992. The effects of being a newborn on otoacoustic emissions. *The Journal of the Acoustical Society of America,* 91**,** 2409-2409.

NORTON, S. J., GORGA, M. P., WIDEN, J. E., FOLSOM, R. C., SININGER, Y., CONE-WESSON, B., VOHR, B. R. & FLETCHER, K. A. 2000a. Identification of neonatal hearing impairment: summary and recommendations. *Ear Hear,* 21**,** 529-35.

NORTON, S. J., GORGA, M. P., WIDEN, J. E., FOLSOM, R. C., SININGER, Y., CONE-WESSON, B., VOHR, B. R., MASCHER, K. & FLETCHER, K. 2000b. Identification of neonatal hearing impairment: evaluation of transient evoked otoacoustic emission, distortion product otoacoustic emission, and auditory brain stem response test performance. *Ear Hear,* 21**,** 508-28.

PENNER, M. J., GLOTZBACH, L. & HUANG, T. 1993. Spontaneous otoacoustic emissions: measurement and data. *Hear Res,* 68**,** 229-37.

PENNER, M. J. & ZHANG, T. 1997. Prevalence of spontaneous otoacoustic emissions in adults revisited. *Hear Res,* 103**,** 28-34.

PICTON, T. W., JOHN, M. S., DIMITRIJEVIC, A. & PURCELL, D. 2003. Human auditory steady-state responses. *Int J Audiol,* 42**,** 177-219.

PROBST, R., LONSBURY-MARTIN, B. L., MARTIN, G. K. & COATS, A. C. 1987. Otoacoustic emissions in ears with hearing loss. *Am J Otolaryngol,* 8**,** 73-81.

RHODES, M. C., MARGOLIS, R. H., HIRSCH, J. E. & NAPP, A. P. 1999. Hearing screening in the newborn intensive care nursery: comparison of methods. *Otolaryngol Head Neck Surg,* 120**,** 799-808.

ROBINETTE, M. S. & GLATTKE, T. J. 2002. Transient evoked otoacoustic emissions. *In:* ROBINETTE, M. S. & GLATTKE, T. J. (eds.) *Otoacoustic emissions: clinical applications.* 2. ed. ed. New York: Thieme.

ROESER, R. J. 1996. *Roeser's audiology desk reference. A guide to the practice of audiology.,* New York, Stuttgart, Thieme.

RUGGERO, M. A., RICH, N. C., RECIO, A., NARAYAN, S. S. & ROBLES, L. 1997. Basilar-membrane responses to tones at the base of the chinchilla cochlea. *J Acoust Soc Am,* 101**,** 2151-63.

SHERA, C. A. & GUINAN, J. J., JR. 1999. Evoked otoacoustic emissions arise by two fundamentally different mechanisms: a taxonomy for mammalian OAEs. *J Acoust Soc Am,* 105**,** 782-98.

SIEGEL, J. H. 1994. Ear-Canal Standing Waves and High-Frequency Sound Calibration Using Otoacoustic Emission Probes. *Journal of the Acoustical Society of America,* 95**,** 2589-2597.

SMURZYNSKI, J. & KIM, D. O. 1992. Distortion-product and click-evoked otoacoustic emissions of normally-hearing adults. *Hear Res,* 58**,** 227-40.

STARR, A., PICTON, T. W., SININGER, Y., HOOD, L. J. & BERLIN, C. I. 1996. Auditory neuropathy. *Brain,* 119 (Pt 3)**,** 741-53.

STAVROULAKI, P., APOSTOLOPOULOS, N., SEGAS, J., TSAKANIKOS, M. & ADAMOPOULOS, G. 2001. Evoked otoacoustic emissions--an approach for monitoring cisplatin induced ototoxicity in children. *Int J Pediatr Otorhinolaryngol,* 59**,** 47-57.

TALMADGE, C. L., LONG, G. R., TUBIS, A. & DHAR, S. 1999. Experimental confirmation of the two-source interference model for the fine structure of distortion product otoacoustic emissions. *J Acoust Soc Am,* 105**,** 275-92.

VON SPECHT, H., GANZ, M., PETHE, J., LEUSCHNER, S. & PYTEL, J. 2001. Linear versus non-linear recordings of transiently-evoked otoacoustic emissions--methodological considerations. *Scand Audiol Suppl***,** 116-8.

WHITEHEAD, M. L., LONSBURY-MARTIN, B. L. & MARTIN, G. K. 1992. Evidence for two discrete sources of 2f1-f2 distortion-product otoacoustic emission in rabbit: I. Differential dependence on stimulus parameters. *J Acoust Soc Am,* 91**,** 1587-607.

WHITEHEAD, M. L., MCCOY, M. J., LONSBURY-MARTIN, B. L. & MARTIN, G. K. 1995a. Dependence of distortion-product otoacoustic emissions on primary levels in normal and impaired ears. I. Effects of decreasing L2 below L1. *J Acoust Soc Am,* 97**,** 2346-58.

WHITEHEAD, M. L., STAGNER, B. B., LONSBURY-MARTIN, B. L. & MARTIN, G. K. 1995b. Effects of ear-canal standing waves on measurements of distortion-product otoacoustic emissions. *J Acoust Soc Am,* 98**,** 3200-14.

WHITEHEAD, M. L., STAGNER, B. B., MCCOY, M. J., LONSBURY-MARTIN, B. L. & MARTIN, G. K. 1995c. Dependence of distortion-product otoacoustic emissions on primary levels in normal and impaired ears. II. Asymmetry in L1,L2 space. *J Acoust Soc Am,* 97**,** 2359-77.

WIER, C. C., PASANEN, E. G. & MCFADDEN, D. 1988. Partial dissociation of spontaneous otoacoustic emissions and distortion products during aspirin use in humans. *J Acoust Soc Am,* 84**,** 230-7.

WILSON, J. & JUNGNER, G. 1968. Principles and practice of screening for disease. *World Health Organization (WHO),* Geneva.

ZWICKER, E. & SCHLOTH, E. 1984. Interrelation of different oto-acoustic emissions. *J Acoust Soc Am,* 75**,** 1148-54.